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The Environmental history and tidal regime of Pattimore’s Lagoon, a modified coastal

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Abstract

Pattimore’s Lagoon is a small coastal lagoon connected to Lake Conjola, an ICOLL (Intermittently Closed and Open Lakes and Lagoon) on the New South Wales South Coast. Prior to 1964 it is believed that Pattimore’s Lagoon was a perched brackish wetland, undergoing a natural transition to an increasingly freshwater system, with tidal exchange limited to large spring tides and unusually high water levels in Lake Conjola. Between 1964 and1984 a number of open channel drains and canals were excavated and an artificial canal estate built along and around the original creek path. This changed the volume, shape and entrance point the canal connecting Pattimore’s Lagoon to Lake Conjola, increasing connectivity between the systems. This increased connection has had considerable effects on the tidal regime within Pattimore’s lagoon and resulted in sediment movement, vegetation changes, and a more variable salinity within the lagoon.

This research examined the types of changes that have resulted within Pattimore’s Lagoon since the 1980s due to the modifications of the tidal regime. Diatoms fossils extracted from sediment cores were used to examine changes in recent salinity and water quality conditions in the lagoon relative to its longer term state. Aerial photographs were used to map changes in vegetation, canal area, and sedimentation within Pattimore’s Lagoon. In addition, the current tidal regime of the lagoon was examined. This combined with precise surveying using differential GPS allowed for an assessment inundation of vegetation zonation around the lagoon. These changes have been assessed with respect to natural variation in Lake Conjola’s entrance condition, which results in changes in the tidal regimes of both the Estuary and Pattimore’s Lagoon.

It was found that Pattimore’s Lagoon has historically and recently been a highly variable system which experienced different salinity regimes in short periods of time. It was also proven that the development of the canal estate did increase the amount of tidal flow into Pattimore’s Lagoon, and this has had an effect on sedimentation and vegetation. The weir, which was installed to return Pattimore’s Lagoon to its pre-Canal state, has been found to have, at least partially, failed. Lastly, it was concluded that currently Pattimore’s Lagoon experiences highly variable salinities and tidal environments. The majority of vegetation around the lagoon has adapted withstand highly variable inundation frequencies and durations. It has been concluded that this is a highly complex and variable system which must be managed in context of Lake Conjola and the wider catchment.

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“The Environmental history and tidal regime of Pattimore’s Lagoon, a modified coastal wetland on the southeast Australian coast”

By

Ashlee Rene Clarke

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The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

- Ashlee Rene Clarke

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Chapter 1. Introduction

1.1 Study Context

Throughout the last few centuries human-kind has influenced almost the entire surface of the planet (Crutzen, 2002). Wetlands and Estuaries have been some of the most heavily affected landscapes, as they are fragile systems easily altered, as well as, desirable landscapes for human settlement (Webster and Harris, 2004). In Australia, estuaries have experienced dramatic transformations since European colonization. Drivers of these changes included dams, river water extraction for irrigation, training walls at estuary mouths, draining wetlands, canal estates, catchment land use, and more. Decreased freshwater flow, altered salinity regimes, altered tidal exchange, and loss of native flora and fauna are only some of the results seen in recent years (Rochette et al., 2010). Due to the dynamic and interconnected nature of estuary systems, changes often induce a chain reaction throughout all the basic functions and ecology of the system (Findlay, 1988, Roy et al., 2001).

Recently, environmental management within Australia has focused on preventing further deterioration of the large-scale changes wrought by relatively recent land use, as well as, restoring systems, where possible, to their natural pre-European states.

The extent of environmental change can only be accurately assessed within a context of the natural, pre-European state of the system with a thorough understanding of how the system functioned. Without long term evolutionary understanding, planners have a very limited knowledge base for management decisions. Within estuaries, this is complicated by the fact that estuarine environments are dynamic systems, which may rarely have long term stable states, i.e., estuary states can be viewed as evolution stages (Sloss et al., 2010), and typically experience high natural variability, in for example salinity (Webster, 2010). In view of the constantly evolving nature of estuaries, management should be based on a detailed understanding of how systems operate over both short and long term (Woodroffe, 2002).

Estuarine management is further complicated by the need to examine the influences of surrounding environments on the system, look at past and current anthropogenic influences and account for long term environmental processes and change. One cannot look solely at the estuarine environment, but must also take into account changes within the entire catchment area, the surrounding ocean, and the larger coastal system (Webster, 2010, Woodroffe, 2002, Zedler, 2011).

It is becoming increasingly obvious that change is ongoing and is to be expected in the future. Therefore it is necessary for planners and decision makers to embrace the understanding that environmental systems are dynamic and change should be anticipated and accepted (Woodroffe, 2002).

Pattimore's Lagoon is a coastal lagoon on the southeast coast of NSW. This system is believed to have undergone substantial changes over the last century due to anthropogenic activity. In its natural state, the lagoon is believed to have been a perched brackish coastal lagoon experiencing limited tidal exchange with Lake Conjola. From the early 1960's, an artificial canal estate was constructed, increasing the connection between Pattimore's Lagoon and Lake Conjola. It is believed this has altered the Lagoon's natural tidal and salinity regime, resulting in changes in water quality and subsequently ecological functioning (Findlay, 1988, Shoalhaven Lakes & Estuaries Management Committe, 1996).

This thesis investigates Pattimore's Lagoon in an attempt to clarify what the natural, pre-European lagoon was like and examine the evidence for recent change in the lagoon, as well as increase the understanding of the current state of the lagoon and how it functions. It is anticipated that this thesis will increase understanding of this system, and will aid decision makers in managing the lagoon effectively. The area surrounding and encompassing the lagoon has been defined as an important natural area by NSW National Parks and Wildlife Services and an important management area in Shoalhaven City Council's 'Lake Conjola Estuary Management Plan' (Shoalhaven City Council, 1998) . It is believed that Pattimore's Lagoon is a unique system with important ecological communities (Findlay, 1988, Shoalhaven Lakes & Estuaries Management Committe, 1996).

1.2 Aims and Objectives

The aim of this project is to investigate the current and historical environment of Pattimore's Lagoon with a view managing the system to improve the environment of Pattimore's Lagoon. To reach this aim within the scope of this thesis, the following objectives will be undertaken;

- Determine the natural state of Pattimore's Lagoon environment before European settlement.
- Determine how the Lagoon has changes due to the development of the canal estate.
- Determine what the current state of Pattimore's lagoon is in regards to tidal regime, salinity, and vegetation.
- Determine the major influences on Pattimore's lagoon and how they vary over time.

1.3 Scope of Research and Approach

In order to provide a broad scientific understanding of the past and present state of Pattimore's Lagoon multiple approaches have been employed. These were designed to examine physical and biological functioning of the Lagoon over multiple temporal scales which included, contemporary, historic and palaeo-history. These scales were deemed most useful for understanding the functioning of the lagoon. Developing a longer term, palaeo-scale (mid to late Holocene) record shows the natural evolution and the variability of conditions which have occurred in the lagoon. The latter is particularly important as no there is no other means of assessing the 'natural', i.e., pre-develop state of the lagoon. Examining the lagoon over a historic scale allows changes in the condition of the lagoon to be mapped. At a contemporary scale, current processes can be compared with those of its natural state, while the processes influencing the present state of the lagoon can be examined. The level of investigation carried out in each case was controlled by the length of study, i.e., what could be achieved within an Honors thesis, as well as availability of data.

In order to investigate the pre-European state of Pattimore's Lagoon sediment cores were extracted from Pattimore's Lagoon. These cores, covering the last 8000 years, were logged and analyzed. Diatom fossils were examined within samples from one of the cores. The diatoms were used to model the past salinity regimes within the Lagoon since it became an isolated system around 3600 years ago.

To examine the changes experienced within Pattimore's Lagoon over the last 50 years, aerial photographs from 1950 -2010 were analysed within the geographical information system ArcGIS to model the type and rate of change experienced within the lagoon. This research was limited by the availability, quality, and resolution of aerial photographs.

The current tidal regime within Pattimore's Lagoon, and the effectiveness of the weir where also investigated. These parameters were investigated because it is believed that the tidal regime of Pattimore's Lagoon has been one of the major factors influenced by the development of the canal estate. Though it is not possible within the scope of this study to model the pre-European tidal regime of Pattimore's understanding the current tidal regime and modern influencing factors could help decision makers understand the current system. The tidal investigation was completed by using tidal recorders in Pattimore's Lagoon, in the artificial channel downstream from the weir, as well as data supplied by Manly Hydraulic Laboratory. This data was then correlated with the various conditions of Lake Conjola's entrance. These findings were then compared to average elevation of vegetation zones around Pattimore's Lagoon to model of the frequency and duration vegetation layers are inundated under different entrance conditions.

1.5 Thesis structure

The introduction of this thesis is followed by a comprehensive literature review (Chapter 2). This outlines the current understanding of estuaries, including estuary definition, and classification models, as well as their evolution, processes and anthropogenic influences. In Chapter 3 the physical settings of Pattimore's Lagoon is described and an extensive summary of the history of the Lagoon is presented.

The methods and results sections are broken into four chapters, each addressing a different aspect of the study . The first, Chapter Four, details the methods and results from the sediment cores and diatom fossil analysis. This chapter investigates the long and short term history of the lagoon. Chapter Five outlines the methods undertaken in the aerial photograph change detection. The results of this section cover the type, quantity and rates of some of the distinct changes seen within Pattimore's Lagoon. Chapter 6 outlines the tidal regime investigation and results. In this chapter, Lake Conjola tidal regime is investigated in context of Lake Conjola's entrance condition. This tidal attenuation experienced between Lake Conjola's entrance and Pattimore's Lagoon is modeled, as well as the effectiveness of the weir. The influence of these factors on the salinity regime is discussed, though time limitations and did not allow for a full investigation. The following chapter, Chapter 7, covers the methods behind the vegetation zone investigation and models the frequency and duration of tidal inundation of distinct vegetation zones under various entrance conditions.

These chapters are followed by a discussion (Chapter 8) which attempts to tie all the investigated areas together and create a comprehensive summary of Pattimore's Lagoon evolution, modern changes and current environment. Finally a conclusion and recommendations (Chapter 9) are presented.

Chapter 2. Literature Review

This chapter discusses estuaries, types of estuaries and some estuarine classification systems. It provides an overview of estuary evolution and describes their processes and functions. Anthropogenic influences on estuaries and their effects are also reviewed.

2.1 Introduction to Estuaries

Estuaries and deltas are similar systems, which are both associated with river mouth processes, have similar morphological processes and are both influenced by fluvial and marine processes. However they are distinctly different systems. Deltas are the accumulation of alluvial sediment at the mouth of a river and form where there is a higher supply of sediment than can be removed by nearshore processes. Estuaries are the tide-influenced lower parts of rivers and are dynamic systems which result from sea level rise and the drowning of low-gradient topography, such as river valleys (Woodroffe, 2002).

In 1967 the committee of American Society for the Advancement of Science defined estuaries by recognizing certain basic similarities in the distribution of salinity and density, circulation patterns, and mixing processes, with a focus on boundaries. This has become one of the most widely used definitions; "*An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage".* (Dalrymple *et al.*, 1992, Potter *et al.*, 2010, Pritchard, 1967). Under this definition, an estuary's salinity range from ~0.1%-35%. Under this definition, coastal water bodies without a fully open inlet at all stages of the tide are defined as lagoons (Pritchard 1967).

This definition was mainly based on temperate, northern hemisphere estuaries, and does not take into account such features such as periodic closure of estuary mouths, coastal lagoons, and hypersaline conditions during dry periods, which are characteristics of Australian and South African estuaries, and the estuaries discussed in this thesis. (Potter et al., 2010)

A 2010 study defined estuaries as *"partially enclosed coastal body of water that is either permanently or periodically open to the sea and which receives at least periodic discharge from a river(s), and thus, while its salinity is typically less than that of natural sea water and varies temporally and along its length, it can become hypersaline in regions when evaporative water loss is high and freshwater and tidal inputs are negligible"* (Potter et al., 2010). This definition is adopted within this thesis.

Estuaries are extraordinarily important systems, which provide ecological, cultural, recreational, aesthetic, historic, and economic value, all of which is expected to increase over time (Friedman, 1977). Environmentally they provide essential fish habitat, especially for juvenile fish, and support a diverse range of species (Rochette et al., 2010). One report of coastal and estuaries economic and market value found estuaries were a priceless asset. A summary of the value of estuaries found within that report can be seen in Table 1.1 (Restore America's Estuaries, 2008).

Table 2.1: Services Provided by Estuaries, adapted from (Restore America's Estuaries, 2008)

Supporting Services	Provisional Services	Cultural Services	Regulating Services
-Supportive Services -Nutrient cycling -Soil Formation Biological -Regulation and Biodiversity -Habitat -Hydrological Cycle	-Water Supply -Food -Raw Material -Genetic -Resources -Medicinal Plant resources -Ornamental Resources	-Recreation -Aesthetics -Science and Education -Spiritual -Historic	-Regulating Services -Gas regulation -Climate regulation -Disturbance regulation -Soil retention -Waste Assimilation

2.2 Estuaries Classifications

Many studies have sought to categorize estuaries, and a variety of classifications systems exist e.g. Roy et al. 2001, Geoscience Australia, Dalrymple et al 1992. Currently there is no comprehensive classification scheme of Australian estuaries, however some commonly used classification scheme of Australian estuaries exist, such as the one depicted in Figure 2.1 (Geoscience Australia, 2012). The Geoscience Australia's estuary classification describes estuary types in terms of a ternary diagram with the type of estuary is defined by the relative contribution of wave, tide and river input. At the top of this graph, are river controlled systems, such as wave dominated deltas and tide dominated deltas. While at the bottom right corner is the most wave dominated system, as Strandplain. It can be seen that estuaries fall within the middle of this diagram, as systems influenced by both rivers and marine processes, though estuaries vary in the amount of influence received from tide and wave processes (Geoscience Australia, 2012).

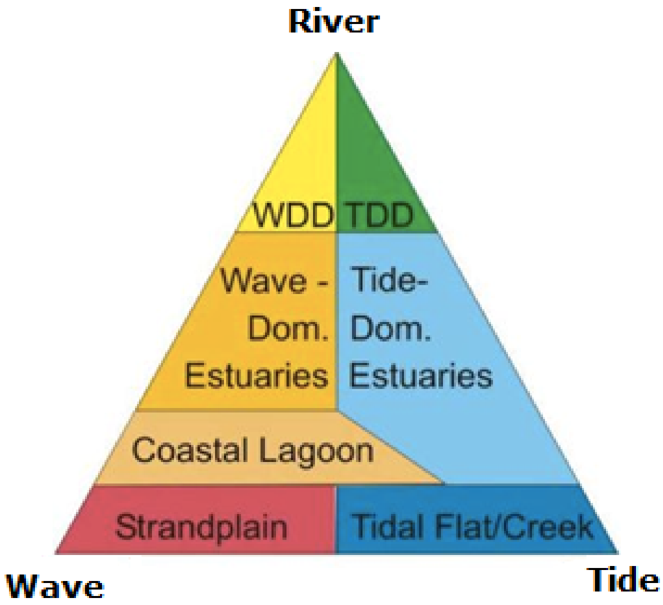


Figure 2.1: Classification of coastal estuaries divided into seven classes, modelled after Dalrymple et al., 1992, and Boyd et al., 1992. (WDD –wave dominated deltas, TDD –tide dominated deltas) (Geoscience Australia, 2012)

Roy et al, (2001) created a sub-set of the wider range of estuary types found throughout Australia, shown in Table 2.2 below, in which estuaries were divided into five categories. This system categorises estuaries on the level of marine influence experienced. In this definition, group I describes semi-enclosed bays characterized by marine waters with little freshwater inflow, a system almost completely dominated by marine influences. While Group V includes all freshwater bodies, which are rarely if ever brackish and have very occasional linkage to the sea. These are systems with arguably no marine influences most of the time. The middle, Groups II – IV represents the most commonly defined 'true estuaries'. These include tide and wave dominated estuaries and intermittently open estuaries (Roy et al., 2001).

Table 2.2: Estuarine categorization system involving five categories based on the level of marine influence. (Roy et al., 2001)

Groups	Types	Mature forms
I. Bays	1. Ocean Embayment's (Botany Bay)	
II. Tide Dominated Estuaries	2. Funnel-shaped macro tidal estuaries (South Alligator River, NT) 3. Drowned Valley Estuaries (Hawkesbury River) 4. Tidal Basin (Moreton Bay)	Tidal Estuaries
III. Wave Dominated Estuaries	5. Barrier Estuaries (Lake Macquarie) 6. Barrier Lagoon (The Broadwater/South Strandbroke Island) 7. Interbarrier Estuary (Tilligerry Creek, Port Stephens)	Riverine Estuaries
IV. Intermittent Estuaries	8. Saline Coastal Creeks (Harbord Lagoon, Sydney) 9. Small coastal creeks (Harbord Lagoon, Sydney) 10. Evaporative Lagoons (The Coorong, SA.)	Saline Creeks
V. Freshwater Bodies	11. Brackish Barrier Lakes (Myall Lakes) 12. Perched Dune Lake (Lake Hiawatha) 13. Backswamp (Everlasting Swamp, Clarence River)	Terrestrial Swamps

Estuaries are controlled by a range of geologic and geomorphic factors in Australia, and are characterised by different tidal exchanges, flushing characteristics, and accessibility for migratory fish and invertebrates. Roy et al. (2001) hypothesised a relationship between multiple physical and chemical conditions in estuaries as well as entrance conditions, which control tidal exchange, salinity regimes, recruitment/migration of biota, and catchment conditions. These in turn influence the shape of the estuary basin, sedimentation rates, present day zonation/ecological habitats, freshwater mixing, nutrient cycling, and survival regimes of the biota.

2.2.1 ICOLLS

ICOLLs are characteristic of the southeast coast of Australia, and in particular NSW. Wave dominated barrier estuaries and coastal lagoons which are intermittently connected to the ocean have been termed 'Intermittently Closed and Open Lakes and Lagoons' or ICOLLs. This type of estuary forms in conditions where there is very little to no river flow, as well as, temporarily variable tidal connections which lead to intermittently or permanently closed entrances. These estuaries are often similar to wave dominated estuaries, but lack a distinct fluvial bay-head delta, or delta at the rivers entrance into the estuary (Figure 2.2) (Geoscience Australia, 2012, Haines and Thom, 2007).

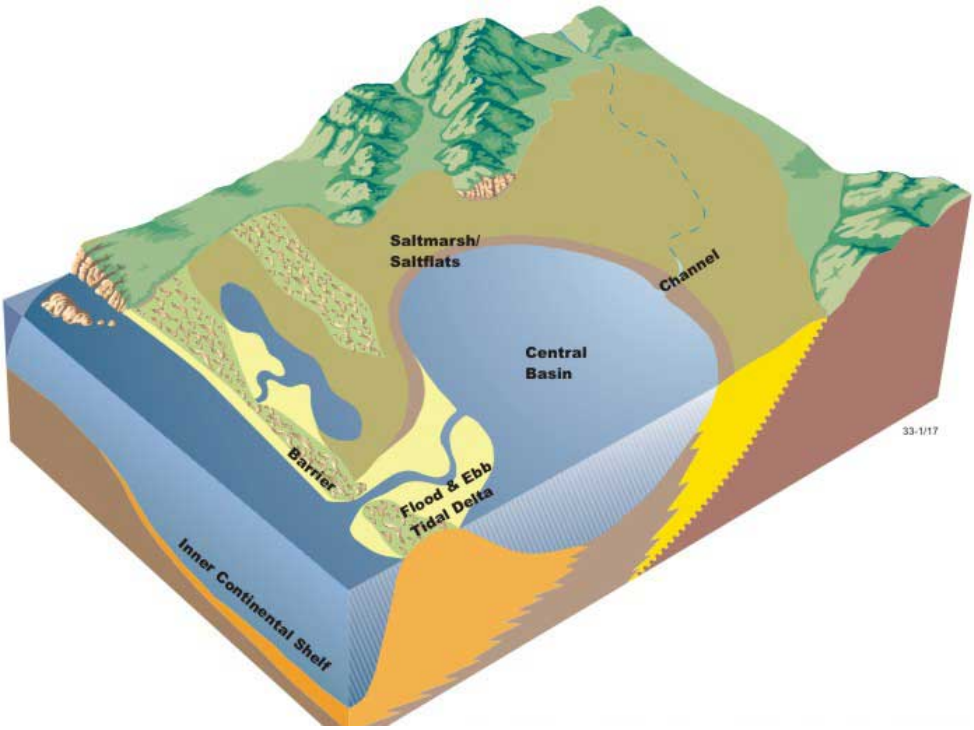


Figure 2.2: Sedimentary environments of ICOLL's. Characteristics to note include, limited freshwater input as well as limited exchange with the ocean, (Geoscience Australia, 2012).

As no universally accepted classification system for Australian estuaries has been accepted, and many of the proposed category systems overlap each other, it is often very difficult to accurately categories Australian estuaries. This situation is further complicated as some estuaries, e.g. Pattimore's Lagoon, maintain elements of multiple categories. Within the Geosciences Australia classification system, which is similar to the Boyd 1992 classification system, Lake Conjola would be a wave-dominated estuary (Boyd *et al.*, 1992, Geoscience Australia, 2012). In Roy et al.'s 2001 estuarine classification model, Lake Conjola would fall between a wave dominated estuary and a intermittent estuary, due to the history of entrance closure for multiple years, and the presence of a fluvial bayhead delta. Lake Conjola will be considered an intermittent estuary, or an ICOLL within this thesis (Findlay, 1988, Haines and Thom, 2007, Roy et al., 2001, Shoalhaven Lakes & Estuaries Management Committe, 1996, Sloss et al., 2010).

Pattimore's Lagoon is more difficult to classify. From a morphological standpoint it could be considered a perched dune lake, however, these are regarded as freshwater systems by Roy et al. 2001 and Pattimore's Lagoon has been recorded to experiences brackish to hyper-saline conditions. Consequently it could be regarded as a saline coastal lagoon (Table 1) (Roy et al., 2001). For the purpose of this thesis, Pattimore's Lagoon will be regarded as a coastal dune deposit, as morphologically this is the most fitting description.

2. 3 Estuary Evolution

Many estuaries are considered to have developed as a result of post glacial sea level rise flooding river valleys and other low-lying areas (Woodroffe, 2002). Sloss et al (2005, 2006, and 2010) developed models for the evolution of southeast Australian estuaries. One of Sloss et al.'s models was based on the evolution of the Shoalhaven River valley to model general pattern for broad barrier estuaries. L later a model of narrow barrier estuaries, based on a study of Burrill Lake and later of Lake Conjola was also developed (Sloss et al., 2010, Sloss et al., 2006). This model shows three major stages in the evolution of these systems (Figure 2.3). Beginning during a sea level low stand, the broad estuary, and narrow estuary would have existed as a remnant interglacial barrier and incised river valley, respectively. As sea level rose during the early to mid Holocene transgression, the systems became flooded. Subsequently, sand barriers developed as rising sea level pushed sand onshore. As sea level stabilised in the mid to late Holocene, following the mid Holocene high stand the estuaries become enclosed by well developed sand barriers. These have persisted until the present with the estuaries experiencing infilling since the mid to late Holocene (Sloss *et al.*, 2005, Sloss et al., 2010, Sloss et al., 2006).

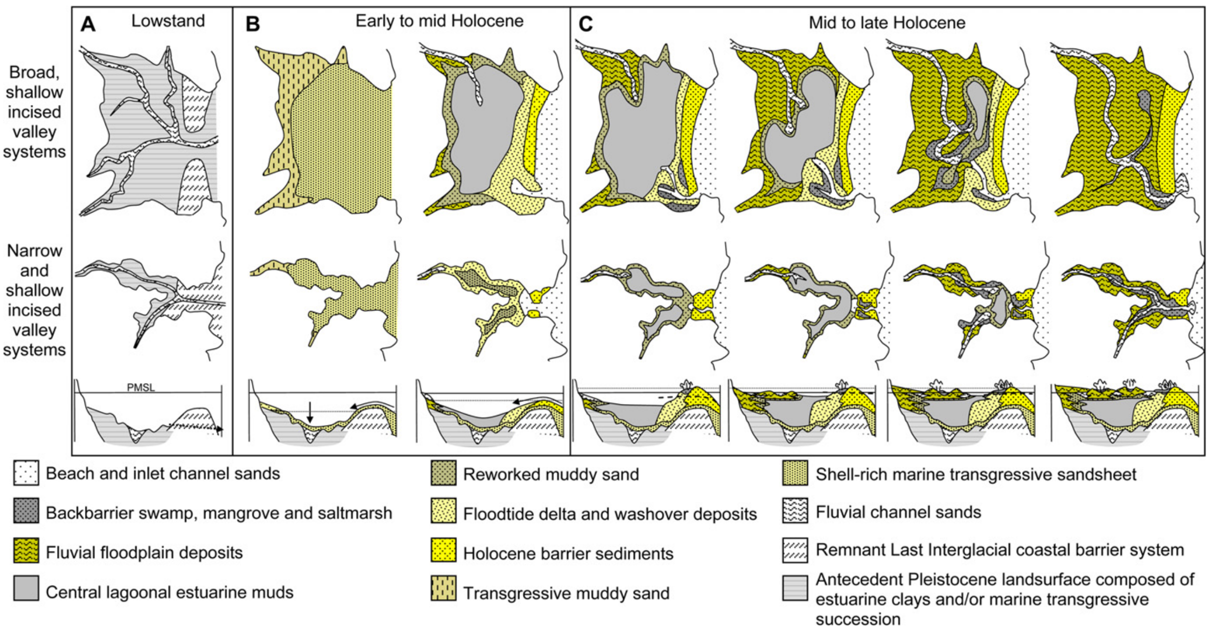


Figure 2.3: Evolution of broad and narrow shallow incised river valley barrier estuaries, (Sloss et al., 2010, Sloss et al., 2006)

One of the studies by Sloss and co-workers used Lake Conjola as a model of estuary evolution, in which, the evolution of Lake Conjola and, subsequently, Pattimore's Lagoon was investigated in detail (Figure 2.4). Firstly Lake Conjola would have developed as a low stand river valley created during low sea levels. During the most recent post-glacial marine transgression (7800 and 6500 yrs BP) the river valley was inundated by rising sea-levels. During the early- to mid-Holocene Lake Conjola would have been received more direct ocean influences and operated as a narrow sheltered coastal embayment or drowned river estuary. At this time a Holocene marine transgressive sand sheet was deposited. The next stage of development resulted from the stabilization of sea level leading to growth of a Holocene proto-barrier and the development of the low-energy back-barrier lagoon from around 3000 years ago. This restricted the open marine influence. The last stage involved further restrictions of marine influences associated with the fully emergent Holocene barrier, the shoaling of the inlet channel, and the initiation of the progradation of fluvial bay-head deltas from ~3000 years BP. Pattimore's is thought to have been cut off from the estuary as it infill's created an isolated lagoon with only a narrow creek leading to Lake Conjola to relieve fresh water overflow. (Sloss et al., 2010).

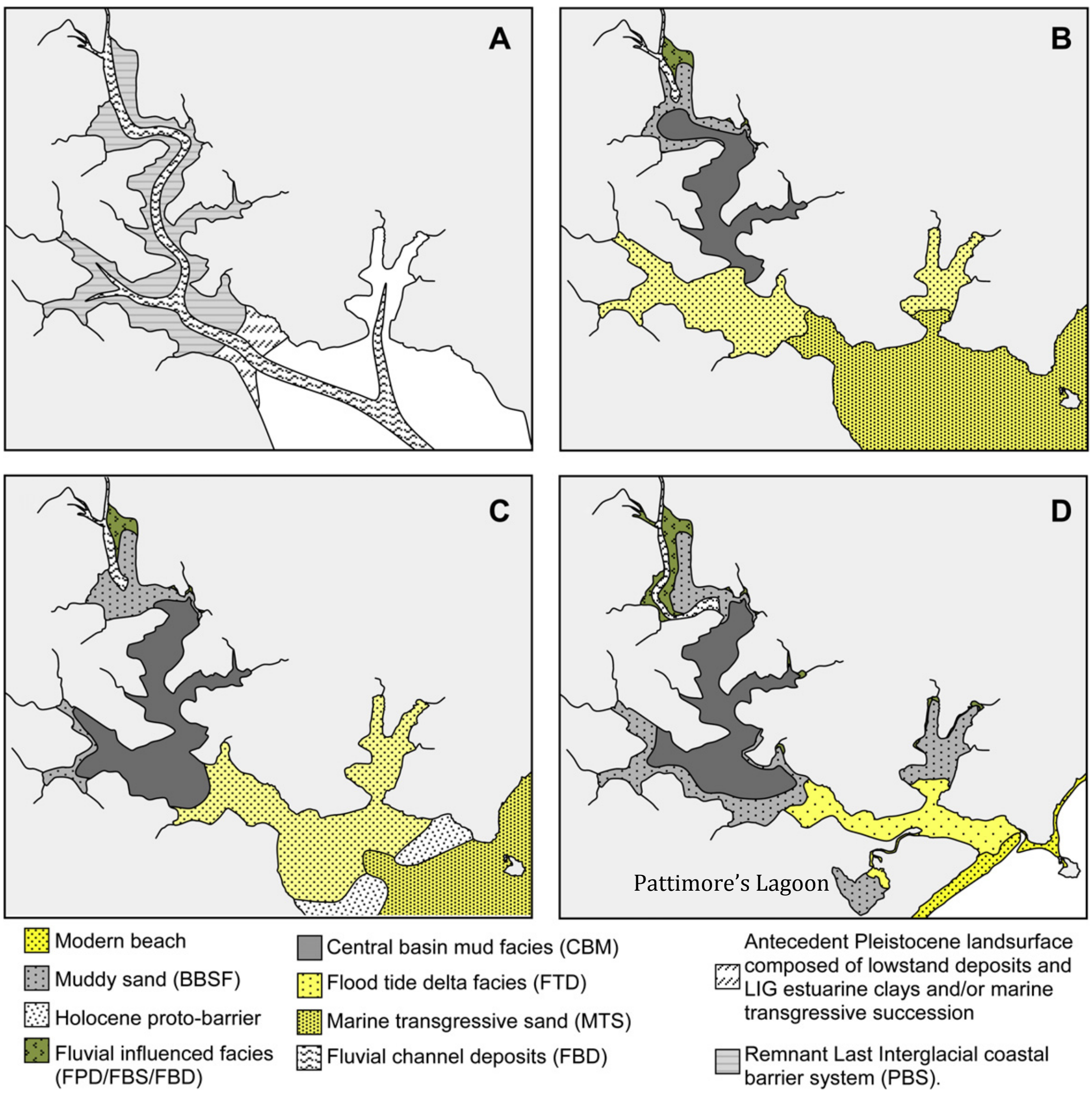


Figure 2.4: Diagram of the geomorphic evolution of Lake Conjola, Lake Berringer, and Pattimore's Lagoon. (Sloss et al., 2010).

2.4 Estuarine Processes

Estuaries are complex, dynamic systems, which greatly hinders one's ability to categorize and understand the interconnected functions and trends within estuaries. Estuarine processes and ecology are controlled by the estuaries physical and chemical characteristics, which are in turn controlled by geological setting, marine and fluvial influences, and evolutionary history (Roy et al., 2001).

Estuaries experience a complex range of climatic tidal, wave, and fluvial processes influencing entrance conditions, water quality, level of maturity, size, and ecology. Estuarine processes are constantly changing, while changes in the one function within a system can have dynamic effects on all other aspects of the estuary over time leading to many different types and states of estuaries both around the world and along the SE coast of NSW (Roy et al., 2001, Woodroffe, 2002).

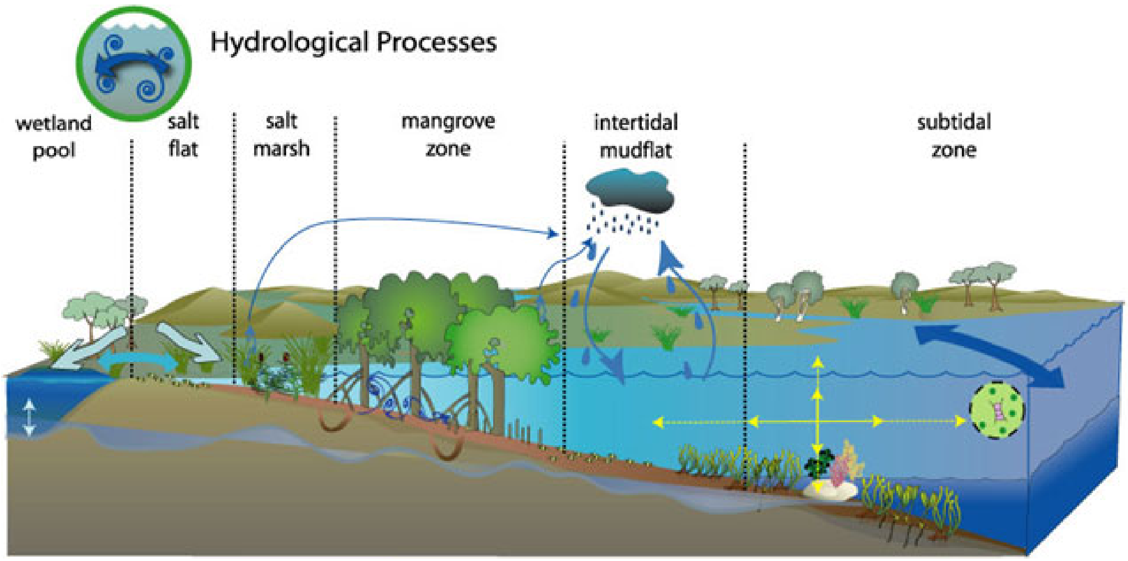
Over long-term time scales, decades to centuries, species assemblages and ecological processes respond primarily to changes in maturity or the level of infilling experienced by an estuary (Roy et al., 2001). The depositional environments of estuaries are characterized by different substratum conditions, hydrological regimes, and nutrient cycling, creating habitats and influencing the species assemblages present within the estuary (Roy et al., 2001, Sloss et al., 2010) In Sloss et al.'s model above, it can be understood that Lake Conjola, and Pattimore's Lagoon would have experienced very different environmental conditions and ecological processes during the different stages of development.

2.4.1 Hydrology and Tidal Regimes

Mitsch and Gosselink in 1993 (quoted by Hughes et al., 1998) stated that *"hydrology is probably the single most important determinant of the establishment and maintenance of specific types of wetlands*".

The principles of hydrology govern the movement and distribution of water. Hydrological principles mostly apply to estuaries, with one major difference; the bi-directional water flow due to tides (Woodroffe, 2002). Hydrological characteristics, such as spatial variability, temporal variability, forcing mechanisms, e.g. spring tide pumping, ad extreme events are key determinant in species distribution, wetland productivity (biomass produced per unit time) and nutrients cycling and availability (Schoellhamer, 2009, Woodroffe, 2002). Hughes et al. (1998) modeled intertidal zone hydrology and found the relationship between hydrology and estuarine wetland ecology is critical in predicting and managing change in wetland environment. These types of changes include long term changes such as climate change and sea level rise, as well and short term changes such as human interferences, i.e. hydraulic modification of tidal flow (Hughes et al., 1998). Figure 2.5 shows some of the hydrological processes that influence estuaries, however this figure is not exhaustive (Geoscience

Australia, 2012). The hydraulic processes which influence estuaries include rainfall, surface water runoff, ground water infiltration and exchange, evaporation, tides, fresh and saltwater mixing, and influencing factors such as vegetation and animal burrowing.



Surface water flows off the catchment into wetland pools and the estuary	Precipitation	Freshwater and marine water are mixed and exchanged in estuaries
Groundwater - surface water exchange (Winter, 1999)	High tides, storm surges, floods and run-off events connect wetland pools to estuaries (Sheaves et al, 2006)	Crab burrows alter water flows (Ridd, 1996)
Tides - including spring and neap	Evaporation from water bodies	Evapotranspiration from vegetation (Hughes et al, 1998)

Figure 2.5: Generalised process model of estuary hydrological processes (Geoscience Australia, 2012)

Within ICOLLs, hydrology becomes more complex due to the changes in entrance condition, which influence tides and other hydrological processes. Generally, ICOLLs have two different hydrodynamic regimes, one when the entrance is open, and another when the entrance is closed (Haines, 2008). When the entrance is open, the system operates as a normal coastal water body. When the entrance is closed, the system becomes a reservoir, and is mainly influenced by catchment runoff, direct rainfall, evaporation, and percolation through sand dunes. These factors in turn effect vegetation inundation, water quality, ecology, salinity, etc (Haines, 2008). A generalised diagram of the main hydrology within an ICOLL is depicted in Figure 2.6, however more processes can be present in individual estuaries (Geoscience Australia, 2012).

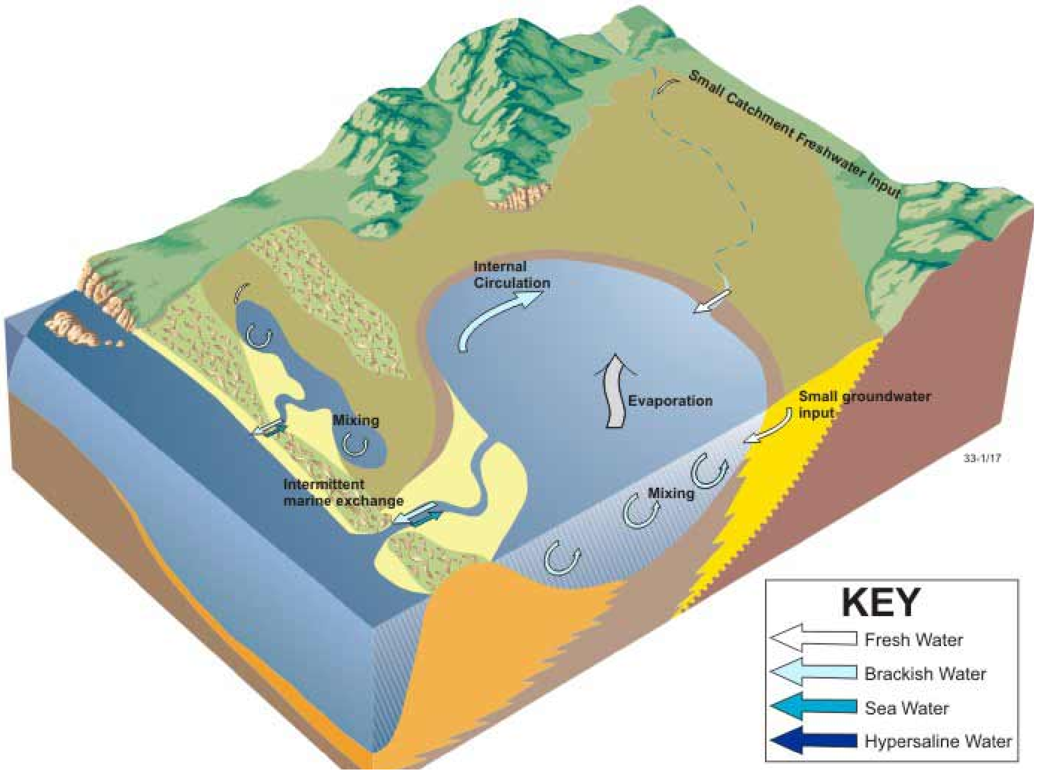


Figure 2.6: Diagram of the hydrology within a ICOLL. (Geoscience Australia, 2012)

Tidal Regimes

Tides are long waves, with a typical periodicity of 12 hours 25 minutes, which are driven by the gravitational pull of the moon and the sun. Tides are found on almost all coasts, though they vary in size greatly from under 2m in some areas to greater than 8m in others (Woodroffe, 2002).

Some estuaries are dominated by tidal currents and display distinct tide-dominated landforms such as tapering channels and intertidal flats in tide dominated estuaries. Tides can become distorted within some estuaries due to frictional dampening, landward constriction of the channel, and reflection from channel banks, shoals and channel head (Geoscience Australia, 2012, Woodroffe, 2002). In the open ocean, tides occur as long waves, gaining maximum velocity at high and low water. Depending on channel geometry, tides in estuaries show standing or progressive wave behavior and in many estuaries show elements of both, and often maximum velocity is experienced at mid tide or just before high tide. A standing waves oscillates at a set point without transmitting energy into the surrounding, while a progressive wave transfers energy from one part of a medium to another (Woodroffe, 2002). In long estuarine channels progressive wave tides can occur, and the water levels in the open ocean and estuary will not be contiguous. In addition, it takes time for the tidal wave to travel along the estuary. The rate of tide movement upstream is related to water depth, and since water depth is greater at high tide, the tidal crest (high tide) travels faster up the estuary than the trough (low tide) (Woodroffe, 2002). This leads to a scenario where the duration of the flood limb gets shorter upstream and the ebb limb gets longer, as can be seen in Figure 2.7.

In estuaries with highly constricted entrances, as seen in ICOLLs, the tidal distortion can be a major factor in the hydrology of the estuary and can vary with entrance conditions. In some estuaries, other controlling factors such as spring tide pumping can become dominate forces. Spring tide pumping is a 14 day cycle which results in a fluctuation of mean water levels in an estuary over a neap to spring to neap tide cycle. As the tidal range increases there is a flow of water into the estuary and as the tidal range decreases in the second half of the cycle, there is a net flow out of the estuary (McLean and Hindwood, 2011).

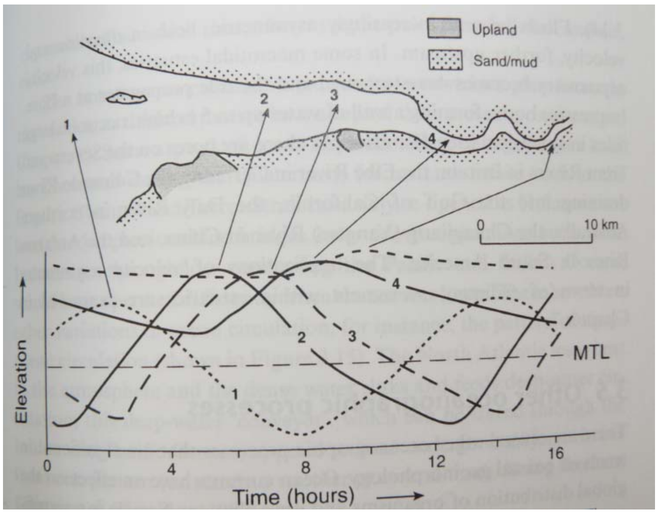


Figure 2.7: Diagram of distortion of tidal wave propagating up a schematic estuary. It can be seen that the tidal amplitude varies as a result of changes in width. (Woodroffe, 2002)

2.4.2 Estuary Connections

The connections between estuaries and other systems are extremely important factors in the functioning of these systems. In Australia, 68% of estuaries are located in wet or dry tropics or subtropics, where, rainfall, and thus freshwater flow, is highly episodic (Sheaves and Johnson, 2008). This leads to many of the estuary and wetland connections being unpredictable, and some systems can be isolated for long periods of time, leading estuarine wetlands and lagoons to experience diverse salinity regimes (Sheaves and Johnson, 2008).

A study by Sheaves and Johnston (2008) looked at the importance of tidal and physical connections in Fitzroy's delta estuarine wetland pools. It was found that the pattern of physical connection and isolation was a critical determinant of the nature of fish assemblage composition and development over time. A graph of the important variables for extinction and recolonisation from this study can be seen in Figure 2.8. (Sheaves and Johnson, 2008). This figure shows the various level of importance factors play in the level of extinction or recolonisation of fish populations in estuarine wetland pools. It can be seen that the salinity regime is the number one factor in determining extinction, while estuary connection distance is is the number one affecting recolonisation. It is interesting to note that the salinity regime, or set of salinity conditions, is more important the salinity range (Sheaves and Johnson, 2008).

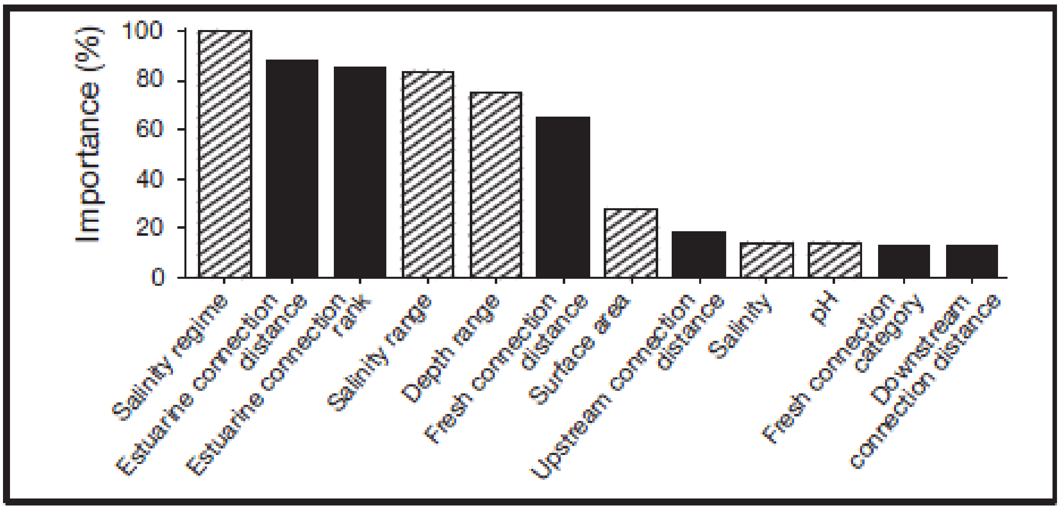


Figure 2.8: Graph of the relative importance of 12 variables in extinction and recolonisation for Fitzroy delta estuarine wetlands pools. Hatched bars describe the extinction variables and black bars describe recolonisation variables. (Sheaves and Johnson, 2008)

Naturally, major floods, tidal connections, and rainfall are the primary drivers behind physical connections of this kind (Sheaves and Johnson, 2008). However, in many modern estuarine system, connections to areas have been modified for human usage, leading to degradation or change in some estuaries.

Along the southeast coast of Australia, over 60% of estuaries are ICOLLs. These types of estuaries often have weak or periodic river flow. It is often seen that during wet periods, river flow is able to maintain an open entrance, but in periods of reduced freshwater flow or increased storm wave conditions, entrances can become blocked by sands. In a natural system, the entrances would remain closed until water levels in the lakes build up high enough to break through the barrier. In these scenarios water breakout would often scour out the entrance, and open entrance conditions would resume until wave conditions and low flow lead to another closure. (Haines and Thom, 2007, Webster, 2011)

2.4.3 Salinity

Estuaries fluctuate in salinity due to variable inflows of freshwater and saltwater, different mixing currents, evaporation, and altered tidal regimes. These processes in turn depend on estuary maturity, type, entrance conditions, and weather patterns (Roy et al., 2001). Salinity plays a vital role in determining the ecology of estuaries, it has also been seen that higher salinity can lead to higher diversity of mangrove species, large saltmarsh area, and diverse fish and invertebrate communities, while brackish and freshwater systems sustain diverse and important ecosystems of their own (Roy et al., 2001).

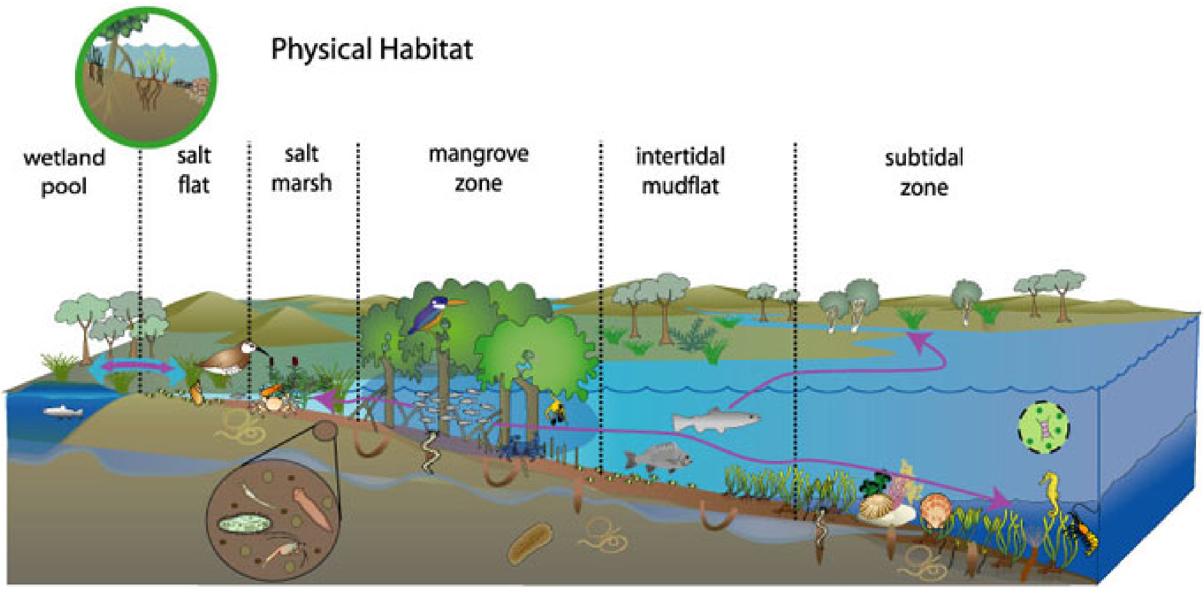
A study in 2008 Nielsen et al. simulated gradual and sudden increases in salinity in wetland environments in order to assess the effects of salinity change on species assemblages. It was found that salt concentrations below 1000mg/L or 1ppt, resulted in species rich communities and individuals resembled freshwater communities, but as salinity exceeded 1000mg/L (1ppt), the diversity rapidly decreased and at 5000mg/L (5ppt), few freshwater species remained. It was then recognized that over 5000mg/L (5ppt) salinity, wetlands would need to be re-colonised by salt-tolerant species for the wetland functions to continue. (Nielsen et al., 2008).

ICOLLs experience highly variable salinities and through this contain very diverse ecological assemblages which change to adapt to current salinity regimes. This results in colonization by estuarine invertebrates and other 'euryhaline', aquatic organisms, species which can withstand a wide range of salinity conditions. High mortality rates of marine species are often observed during periods of entrance closure. These periods proved an opportunity for estuarine and low salinity species recruitment into the estuary. In turn, periods of open connection with the ocean lead to re-population by marine species (Geoscience Australia, 2012). ICOLLs are important habitats for a diverse assemblage of juvenile fish, as well as macro-algae, some seagrass and saltmarsh beds and floodplain species. Mangroves typically do not occur in lagoons with long periods of closure due to the restricted ocean connection, but have been seen in some estuaries (Geoscience Australia, 2012).

2.4.4 Biological Processes

The biological processes within estuaries vary greatly with the type of estuary system. Some of the common biological processes can be seen in Figure 2.9 (Geoscience Australia, 2012).

In tide dominated estuaries, a large variety of habitats exist. There also tends to have greater plant productivity with increasing tidal range due to the rates of flushing and thus greater renewal of nutrients. In these system mangroves tend to be prevalent, as well as grasses, sedges, freshwater wetlands, and floodplain vegetation (Geoscience Australia, 2012). Wave dominated estuaries also contain a wide range of habitats. These systems contian "true estuarine' or euryhaline species (species with wide ranging salinity tolerances), as well as transient marine species (Geoscience Australia, 2012). In open embayment's, the biological systems are somewhere between true estuarine and marine, and contain highly variable species (Geoscience Australia, 2012).



Small fish move with the tides to access mangrove areas, where they find protection, and to the salt marsh, where some feed (Connolly et al, 2006)	Mangroves shade water and sediment, buffering temperature and blocking UV radiation, providing a habitat for other organisms (Hsieh, 1995)
Some fish move upstream and downstream, to fresh and marine water habitats at different stages of their life cycles to breed and spawn (Robins et al, 2006)	 Mangroves are important nursery areas for some juvenile fish and crustacean larvae (Blaber, 2000; Beck et al, 2001)
Water flow between wetland pools and estuaries during very high tides or run-off events allows fish to move between these habitats (Sheaves, et al 2006)	 Many organisms in estuarine wetlands live in burrows or on the sediment, including worms and microbes

Figure 2.9: Generalised process model of physical habitat within estuaries, Geosciences Australia, 2012.

Within ICOLLs and coastal lagoons the entrance condition, i.e. open, partially shoaled, nearing closure, closed, is believed to be the most important factor influence on biology. These system are known as ecotones, or systems which provide habitat for both freshwater and marine species, as well as euryhaline species (Haines, 2008). In periods of closure there is often a high level of marine species mortality, which provides opportunity for estuarine and low salinity species to recruit and colonise the system. Even very small coastal lagoons are important habitat for a diverse range juvenile fish (Geoscience Australia, 2012).

Within ICOLLs seagrass cover is highly dynamic due to the significant changes in water level experienced. Seagrass relays on light penetration through water, and change in extent in response to light availability. At a certain point, water level variations in some systems become too rapid for seagrass to adjust, and in these system seagrass tends to be absent (Haines, 2008).

Mangroves are rarely found within ICOLLs, and tend only be found in ICOLLs which are primarily open systems. However, some exceptions exist, mainly along north coast of NSW. In these system mangroves have adapted to exist in mainly closed systems through morphological adaption's such as developing pneumatophores over a meter in length (Haines, 2008).

As many estuarine wetlands species rely on periodic inundation, often by saline water, to remain competitive against terrestrial species, artificially opening ICOLLs, which reduces the natural water level range, often results in a reduction of estuarine vegetation and wetlands communities (Haines, 2008).

Around Australia, and other parts of the world, a encroachment of mangroves landwards within estuaries has been observed over the last 60 years (Saintilan and Williams, 1999). The landward movement has been attributed to a variety of factors including altered tidal regimes, hydrological variations, sea level rise, increased precipitation, subsidence, altered sedimentation and nutrient levels and cessation of agricultural practices (Eslami-Andargoli et al., 2009, Jones et al., 2004). These changes affect propagule dispersal as well as the suitability of the environment for mangrove establishment (Breitfuss *et al.*, 2003, Jones et al., 2004, Saintilan and Williams, 1999). In NSW mangrove expansion has been attributed to changes in tidal regimes due to modifications of entrance conditions and dredging, as well as to a small eustatic sea-level rise experienced along the Australian east coast over the last 100 years (Saintilan and Williams, 1999).

2.5 Anthropogenic influences

Currently, the forces of the man-kind have become "*as powerful as many natural forces of change, stronger than some, and sometimes as mindless as any*" (Meyers 1966 p. 2 quoted in Woodroffe, 2002 p.476).

Anthropogenic influences on estuaries across the globe include changes such as, but not limited to; increased sedimentation, introduction of pollutants, eutrophication, changes in catchment runoff, increased or decreased connection to the ocean, removal of mangroves, introduction of invasive species, drainage of wetlands and artificial channels. These changes have influenced the processes, functions, and ecology of many of these systems, sometime past repair (Crutzen, 2002, Webster and Harris, 2004). As the influence of societies on coastal systems increase with rising populations and human induced climate change, environmental management will have to become increasingly focused on sustaining natural processes and balances in the face of human induced changes (Haines and Thom, 2007). ICOLLs and coastal lagoons are generally recognised as the most sensitive estuaries due to their irregular connection with the ocean and limited tidal exchange. In researching coastal systems, and understanding future processes, it is becoming increasingly important to incorporate human influences into environmental models (Woodroffe, 2002).

A 2007 study on the Mondego estuary, on the Atlantic coast of Portugal, assessed the long-term ecological response of a macrobenthic community and the different effects of natural verses human induced disturbances (Dolbeth et al., 2007). During the study periods, two large anthropogenic influences occurred. Firstly, there was extensive eutrophication which lead to rapid growth and macroalgae blooms, and siltation which limited flow in the upstream areas and lead to a complete separation of the north and south arms of the river. Secondly, mitigation measures were implemented in the construction of a channel between the two arms, which allowed water flow during high tide. In addition to these changes, natural disturbances were experienced in the form of extreme climatic events, in which a centenary flood occurred in 2000-2001, and a severe drought occurred in 2005 (Dolbeth et al., 2007). This study found that the benthic communities were able to recover more easily after the extreme climatic events than the anthropogenic disturbances. The climatic events influences diminished immediately after the event, and the community was able to recover and even improve their environmental quality. The anthropogenic disturbances were considered to have longer lasting effects on marcobenthic communities, despite natural events having significant impact over a shorter time, the human induced change had larger cumulative effects on the ecosystem's health, and lead to permanent deterioration (Dolbeth et al., 2007)

Often, interference with estuarine functioning can lead to increased need for maintenance and further management. One excellent example of human modifications to an estuarine system leading to increased need for intervention is The Coorong in South Australia (Webster, 2011). The Coorong is part of a lake system involving Lake Alexandrina, Lake Albert, the Murray mouth, and the north and south Coorong. A line of barrages were installed to separate Lake Alexandrina from The Coorong to prevent saline intrusion in to the lakes and lower Murray and to maintain higher water levels then in the natural systems. During times of high water discharge, freshwater flows over the Barrages and maintains an open mouth entrance to the Murray and thus the Coorong (Webster, 2011). However, during times of low river discharge no water flows over the barrages and the entrance can close, leaving The Coorong isolated from other system. From 2001-2011, drought caused salinity in The Coorong to reach four times that of seawater. To counter this, a entrance dredging program has had to be implemented, and now dredging has been found to be the major determinant of the ecological condition of The Coorong (Webster, 2011).

2.5.1 Entrance conditions

In NSW, over 60% of estuaries are ICOLLs. The entrance conditions of these systems are dependent on local setting, such as size, orientation of the embayment and headlands, availability of sand, rainfall/freshwater inflow, ocean wave climate, and tide variance. The systems are controlled by the balance between wave processes and flood tides which move sediment into the entrance, and the ebb tide and fluvial processes which move sediment out of the entrance (Hanslow et al., 2000, Stephens and Murtagh, 2012). These pattern of entrance opening and closing influences water quality, salinity, tidal regimes, and ecology of estuaries. (McLean and Hindwood, 2011, Roy et al., 2001).

Recently many communities in NSW maintain the perception that an open estuary is a natural estuary, and a closed estuary is a 'sick' or unhealthy estuary. This combined with nuisance flooding during estuary closure, the desire for navigable entrances for boats, actual or perceived water quality problems, and perception that opening entrances will increase fish and prawn recruitment, has led to many communities demanding that entrances be manually opened and kept open. Artificial entrance walls and dredging programs are commonly seen in many of NSW's estuaries. However, research has found that there is no ecological need for permanently open entrances and often estuary closure is part of a natural cycle, which should be left to continue (Stephens and Murtagh, 2012).

It has also been shown that some estuaries opening can even have negative impacts on estuaries such as;

- Changes in vegetation due to increase and stabilisation of salinities.
- Changes in hydrology can decrease the health of fringing wetlands such as endangered -ecological communities of coastal saltmarsh which rely on periodic inundation.
- Introduction of anoxic conditions leading to fish kills.
- Reduction of fish habitat, such as removal of sea grass beds, leading to reduction in fish stock.
- Reduced opening duration due to inefficient scour of entrance at low opening levels.

(Stephens and Murtagh, 2012)

In some cases, entrance closure can have benefits, such as seen in Lake Conjola with the recent reduction of *Caulerpa taxifolia*. *Caulerpa taxifolia* is a fast growing alga native to India which has become a major invasive species across the globe. Lake Conjola is one of nine waterways infested on NSW's coast. Figure 2.10 shows the extent of the infestation. It can be seen that *Caulerpa taxifolia* extends over the whole of Lake Conjola and all of its tributaries and bays except Pattimore's Lagoon upstream of the Lake Conjola Entrance Road (Department of Premier and Cabinet, 2011).

A study in 2007 examined the effect of water temperature and salinity on the growth and survival of *Caulerpa taxifolia* (West and West, 2007). It found that *Caulerpa taxifolia* grew quickly at temperatures above 15° C and salinities above 22.5ppt. There was almost total mortality at salinities under 17.5, indicating that this species is mainly a marine alga which would be not survive well under long periods of low salinity. Historically, Lake Conjola has experienced long term periods of entrance closure which have lead to low salinity levels within the lake, with salinities of under 17ppt for two years in the late 90's (West and West, 2007). However, recent efforts to maintain a permanently open entrance have lead to salinities close to marine, maintaining optimum growing conditions for *Caulerpa taxifolia.* West and West (2007) suggest the option of returning the lake to its natural opening regimes with long periods of closure, which would have strong negative impacts on the *Caulerpa taxifolia* infestation. A reduction of *Caulerpa taxifolia* has been observed within Lake Conjola recently as a result of the failed entrance openings allowing Lake Conjola to sufficiently freshen.

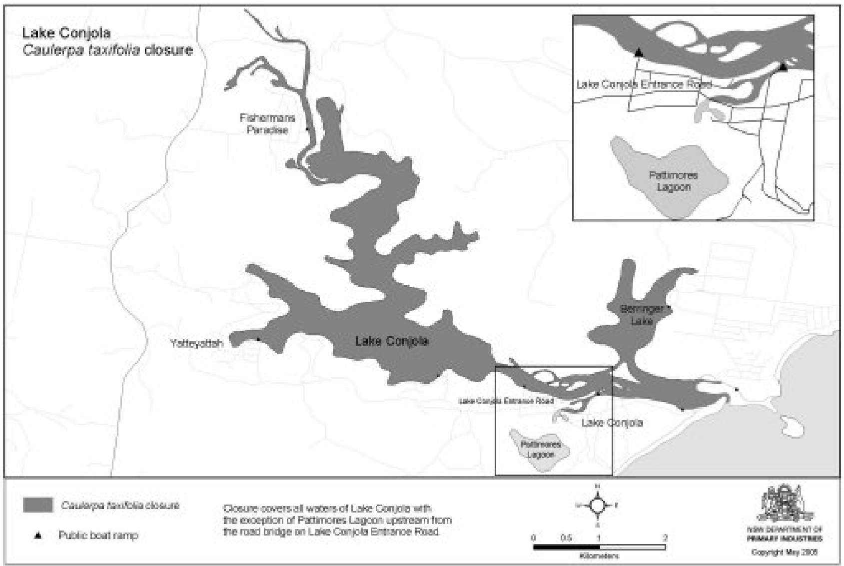


Figure 2.10: Map of extent of *Caulerpa taxifolia* in Lake Conjola. This image shows *Caulerpa taxifolia* extending over the whole of Lake Conjola and its tributaries and bays other than in Pattimore's Lagoon upstream of the Lake Conjola Entrance Road (Department of Premier and Cabinet, 2011).

Another study which has looked at the negative impacts of entrance opening assessed changes in fish species within Peal Harvey Estuary in southwest Australia after the installation of an artificial second entrance channel (Young and Potter, 2003). Due to agriculture and land management practices Peel-Harvey estuary had become highly entropic and developed large macro-algae blooms. Authorities decided to build a second artificial entrance channel to increase tidal flushing and reduce the amount of eutrophication and algal growths. This has led to large scale changes throughout the estuary. Samples of fish collected before the artificial channel 1980 and 1981 and after the channel, 1996-1997 were used to assess the extent of changes. The installation of the channel was accompanied by a reduction in the abundance of fish, especially fish associated with macro-algae, a decline in the number of fish species present, a decline in inter-annual differences in species richness and abundance, increase in marine species within the estuary and a decrease in differences between regions and the two estuaries. This is believed to be due to the reduction in algae which provided food and shelter, increase in marine influence allowing the entrance of marine species, more stable conditions throughout the estuary over time, and increases tidal flushing facilitating greater dispersals of fish (Young and Potter, 2003).

Lake Innes

A local example of anthropogenic influences affecting estuary functioning comes from Lake Innes Swamp and Lake Cathie on NSW's North Coast (Figure 2.10). These estuaries form a system of interconnected lakes, wetland, and estuarine creek system, which provide a diverse ecological and recreational value to the local community. Lake Innes is believed to have initially been part of Lake Cathie Estuary, and became a separate system 2000-3000 years ago. It is probable, that during very wet periods Lake Innes would have overflowed into Lake Cathie, and when Lake Cathie remained closed to the ocean during periods of high lake water levels, would have overtopped the barrier and connected with Lake Cathie. However, for the most part, Lake Innes would have isolated freshwater system which supported abundant bird life and freshwater species. (Umwelt Environmental Consultants, 2003)

In 1933, a channel was excavated between Lake Innes and Lake Cathie in the hopes of draining Lake Innes to create agricultural land. The channel initiated a chain of events that transformed the large freshwater lake with reed beds, floating peat islands, bird habitats, and freshwater catfish and perch, to an extension of the Lake Cathie and Cathie creek estuary, with saltmarsh, wading birds, and an estuarine fish community. (Umwelt Environmental Consultants, 2003)

Figure 2.11: Lake Innes Shoreline and waterways, December 2002, showing low water levels hypersaline system and dense aquatic plant (Umwelt Environmental Consultants, 2003).

An investigation into the feasibility of returning Lake Innes to a freshwater system started in 1994 with a series of plans and studies. Reasons for closing the lake connections and returning Lake Innes to a natural system include the rarity of natural freshwater lakes the size of Lake Innes and increased regional biodiversity, historic and aboriginal heritage, and the likely increase of natural rainfall driven openings of Lake Cathie's entrance. Cases for leaving the Lakes in their current conditions included; predicted reduction in local commercial fishing with a closure of the connection, negative impacts on the protected estuary cod which resides in Lake Innes, and the findings that a freshwater lake presents a greater risk of invasive species (Umwelt Environmental Consultants, 2003).

In 2003 a management plan found that restoring Lake Innes to a freshwater system, largely separate from the estuary would be a more sustainable management option then maintaining the current situation. In June of 2008, it was announced that the Federal budget has allotted $1 million towards planning and works to revert Lake Innes to its natural freshwater state, and there have been preparations for an EIS of the plan to insure all issues have been examined (Umwelt Environmental Consultants, 2003)

Summary

In summary, estuaries are complex, dynamic systems, which vary greatly over time and space. Australian estuaries are difficult to classify with commonly accepted classification systems due to the prevalence of systems with periodically closed entrances and hypersaline conditions. Estuaries experience a wide range of hydrology, salinities, levels of connectivity, and ecology, all of which change over time and space. Estuaries have been heavily modified throughout the world, modification along the southeast coast of Australia have resulted in a very wide scale changes. As a result, management must focus on managing highly degraded systems, and where possible to restoring systems to natural, pre-European conditions.

Chapter 3. Pattimore’s Lagoon

Chapter 3 includes a description of Pattimore’s Lagoon as well as an outline of the south coast of NSW and more specifically Lake Conjola. This chapter then presents an outline of Pattimore’s environmental history.

3.1 Site Description

3.1.1 Pattimore’s Lagoon

Pattimore’s Lagoon is a relatively isolated coastal lagoon with a surface area of 0.3 km^2 and water depths of up to 3 m, located southeastern coast of NSW, approximately 200 km south of Sydney and 10 km north of Ulladulla. It is part of the Lake Conjola catchment area, and is currently connected to Lake Conjola by a narrow creek and artificial canal estate. (Findlay, 1988, Shoalhaven Lakes & Estuaries Management Committe, 1996) Pattimore’s Lagoon formed in a shallow coastal dune depression. The lagoon is feed by a small freshwater tributary creek. Currently, Pattimore’s is believed to be a highly modified coastal lagoon with conditions heavily influenced by the entrance state of Lake Conjola (Shoalhaven Lakes & Estuaries Management Committe, 1996).

Figure 3.1: Map of Pattimore’s Lagoon, insert map shows the position of Pattimore’s Lagoon within the large Lake Conjola estuary.

3.1.2 Lake Conjola Catchment

Lake Conjola is a wave dominated ICOLL on the southeast coast of Australia, with a surface area of 5.8 km^2 and depths up to 10m. The Lake contains two separate water bodies connected to Lake Conjola by narrow entrances. On the northern end, Lake Berringer is a depositional basin of 0.8 km^2 and depths over 5 m, while Pattimore's Lagoon is on the southern end (Findlay, 1988, Shoalhaven Lakes & Estuaries Management Committe, 1996, Sloss et al., 2010). Lake Conjola catchment 145 km^2 and drains into Lake Conjola via multiple tributaries (Findlay, 1988).

Lake Conjola formed during post-glacial sea level rise when rising ocean levels flooded a narrow incised river valley cut into Permian sandstone. Over time a barrier built up separating Conjola from the ocean creating the current wave dominated barrier estuary. Around the edge of the estuary, the sandstone forms low sub horizontal rock benches and in some areas small cliffs. Inland Lake Conjola is confined by a steep escarpment, the Eastern Highlands, which run roughly parallel to the coastline. Off the coast is a narrow and deep continental shelf (Sloss et al., 2010). The sedimentary layers within Lake Conjola and its basins can be seen in Figure 3.2.

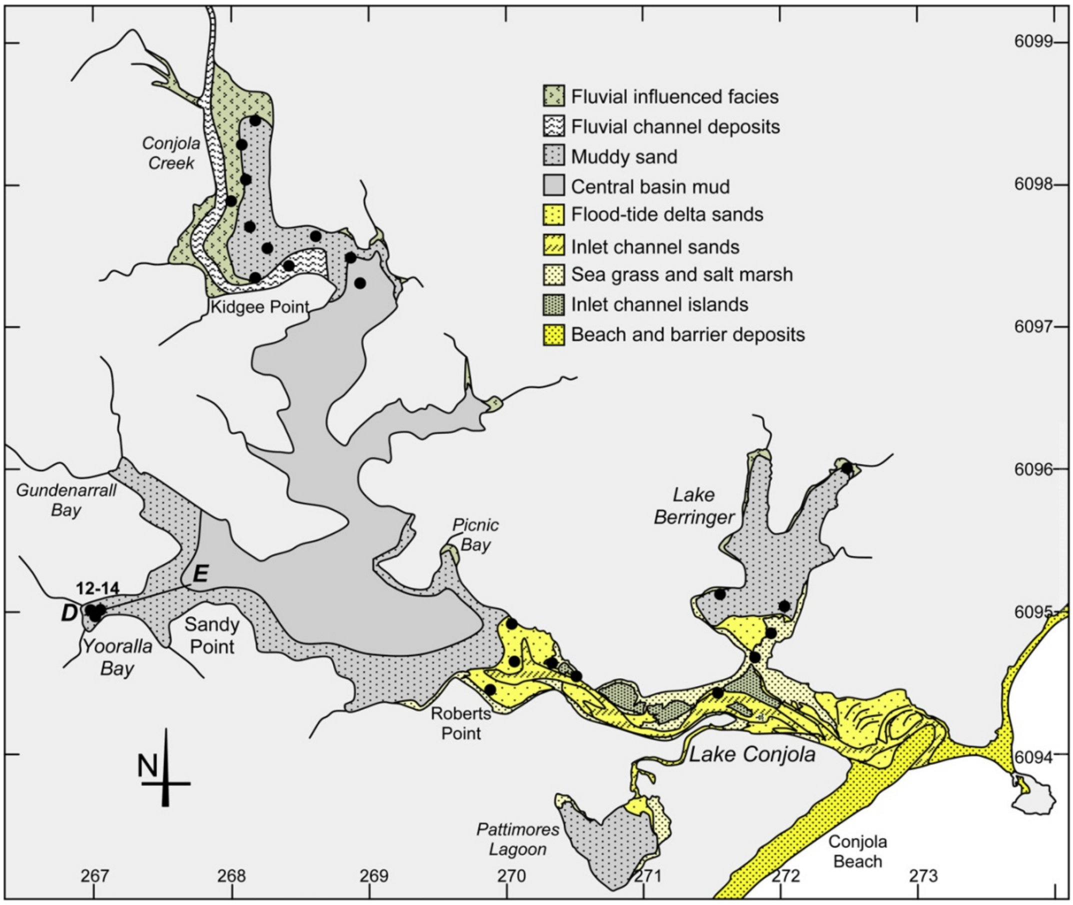


Figure 3.2: Sedimentary facies divisions of Lake Conjola from Sloss et al. 2010.

Temperature data collected from the Ulladulla township, approximately 10 km south of Lake Conjola, show a maximum mean annual temperature of 20.6 ˚ and a minimum mean annual temperature of 13.1˚. Rainfall data from Ulladulla show a mean annual rainfall of 1035 mm, with the highest rainfall occurring between February and June (Bureau of Meteorology, 2012).

The lake is connected to the ocean by a 3.5 km long channel, which reduces the tidal range within the estuary to approximately 20% of the ocean range under typical (open) entrance conditions. Due to geomorphic constriction the average water level in Lake Conjola is 27 cm above average mean sea level (Manly Hydraulics Laboratory, 2003, Sloss et al., 2010). Lake Conjola's entrance varies from a fully open state to fully closed, during which the estuary is not connected with the open ocean (Manly Hydraulics Laboratory, 2003). The level of tidal variation and therefore water level has been shown to vary greatly depending on the entrance conditions of the estuary (McLean and Hindwood, 2011).

Pattimore's Lagoon is less affected by tides then the rest of the estuary due to the long artificial canal estate which connects Pattimore's Lagoon to Lake Conjola, as well as partially collapsed weir at the entrance to the lagoon (Manly Hydraulics Laboratory, 2009).

The Lake Conjola entrance changes constantly due to dynamic interchange between floods, tidal flows, storm waves, littoral sand supply and wind-blown sand from Conjola Beach. The entrance has closed eight times over the last 60 years and has remained closed for periods of up to 4 years, until floods, often assisted by mechanical excavation, reopen the channel. When the entrance is closed, the lake often becomes fresher due to inputs of fresh water, while the lake level increases, however in periods of drought, lake levels can fall and salinity can increase to levels above that of ocean water (Manly Hydraulics Laboratory, 2003).

A study in 2011, Mclean and Hindwood, examined the influence of spring tidal pumping, a fourteen day tidal cycle controlled by spring tides, in Lake Conjola during different levels of entrance shoaling (McLean and Hindwood, 2011). During the study period, Lake Conjola entrance progressively shoaled from an open channel to a highly restricted entrance nearing closure. Consequently, the major tidal influence within Lake Conjola changed progressively from normal 12 hour tidal cycles to fortnightly neap-spring tidal cycle (McLean and Hindwood, 2011).

There has been pressure on the local council to maintain an open entrance in Lake Conjola due to perceptions of water quality and estuarine health during entrance closure (Manly Hydraulics Laboratory, 2003). In 2003 Shoalhaven City Council and the Lake Conjola Estuary Management Task Force adopted the Lake Conjola Entrance Management Plan. The aim of this policy is to "ensure a permanently open entrance with minimal interference with natural environmental processes" (page ii Manly Hydraulics Laboratory, 2003). Under this plan, the entrance is monitored and entrance works, dredging sand from the entrance channel and depositing it on the entrance spit, are carried out in an attempt to prevent closure (Manly Hydraulics Laboratory, 2003). However this policy is currently under review.

3.2 History of Pattimore's Lagoon

It is generally believed that prior to 1964, when canal development began, Pattimore's Lagoon was a perched, brackish wetland, undergoing a natural transition to an progressively freshening lagoon with increasingly complex vegetation. Tidal exchange is believed to have been limited to large spring tides and unusually high water levels in Lake Conjola (Findlay, 1988, Shoalhaven Lakes & Estuaries Management Committe, 1996). However, parish maps from 1893 to 1971 label Pattimore's Lagoon as salt water, indicating that Pattimore's Lagoon has always been a predominantly saltwater system, as can be seen in Figure 3.3 (Land and Property Management Authority, 2012). From 1964-mid 1980s, a number of open channel drains and a canal were excavated along and around the original creek path which connected Pattimore's Lagoon to Lake Conjola, to create a canal estate. This canal estate was arguable poorly designed and did not follow best practice guidelines of appropriate canal estate guidelines, (Cosser, 1989), such as creating channels without dead ends, sharp angles and excessively deep reaches, all of which this canal estate contains (Findlay, 1988). These fundamental problems in the design have restricted water circulation and flushing leading to the accumulation of pollutants and sediments, such as natural and human faecal contamination from leaking sewage effluent systems and absorption trenches. (Catlan and Williams, 1985, Cosser, 1989, Findlay, 1988, Shoalhaven Lakes & Estuaries Management Committe, 1996).

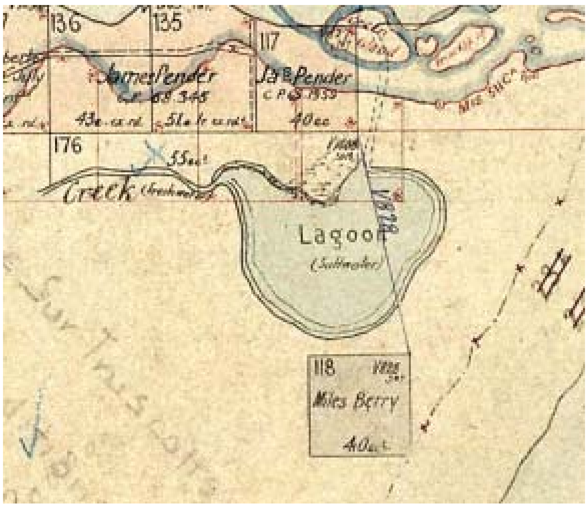


Figure 3.3: Pattimore's Lagoon on 1893 parish map labelled as saltwater from this map to the most recent Parish map in 1971.

The work was undertaken by the company Edge Homes, who went into liquidation in 1976 during construction of the estate and attempted to sell the half built subdivision to National Parks and Wildlife Services and others. The subdivision was bought in 1982 by a new development company, the size and number of lots reduced significantly and construction re-commenced.

The construction of the canal estate is likely to have significantly altered the tidal regime and hydrology of Pattimore's Lagoon, creating a regular tidal link to Lake Conjola. In 1976 environmental concerns about the developments effects on the lagoon were raised and subsequently an artificial weir was placed in the channel near the southern entrance of the lagoon by 1982, as seen in Figure 3.4, with the aim of reducing the tidal exchange in the lagoon and returning the system to the pre-existing condition. In the late 1980's the weir collapsed, reducing its effectiveness. (Shoalhaven Lakes & Estuaries Management Committe, 1996)

Figure 3.4: The weir being installed at the entrance of Pattimore's Lagoon in 1982 by Shoalhaven City Council (image provided by Shaolhaven city council by personal communication).

The tidal regime within Pattimore's Lagoon has been recorded to be around 5 cm, during the course of this study it has been seen to vary from 0-5 cm (see Chapter 6). It is believed that this tidal regime is enough to significantly alter the ecosystem within the lagoon from its pre-existing state, thought supporting data is limited (Findlay, 1988, Shoalhaven Lakes & Estuaries Management Committe, 1996).

In 1987 requests for Shoalhaven City Council to dredge the artificial canal were rejected on the basis that dredging the canal would increase tidal flow. Since the weir had already collapsed at this point, this would increase tidal flow into Pattimore's Lagoon even more, and this was expected to 'significantly affect the environment' (Shoalhaven City Council personal communication, 2012). The 1998 Lake Conjola Estuary Process Study highlighted poor water quality and siltation in the canal as an issue, but it was concluded that upgrading the entire canal to a well designed uniform cross section would increased tidal range to 0.20m and would "impose fatal stress levels" on Pattimore's lagoon flora and fauna (Shoalhaven Lakes & Estuaries Management Committe, 1996). This process study recommended "redesigning the present canal layout to improve tidal flushing and reduce sedimentation, without further modifying the tidal influence of Pattimore's Lagoon" or alternatively "filling in the canals to create parkland and restoring the pre-existing ecosystem in Pattimore's Lagoon",

Summary

Pattimore's Lagoon is a modified coastal wetlands on the southeast coast of Australia. It is a semi-isolated system which is partially connected to Lake Conjola estuary, an mostly open ICOLL which experiences periodic, long term closure. Pattimore's Lagoon was modified from 1960s-1980s by the development of a canal estate which has increased the lagoons connection with Lake Conjola. These changes are believed to have altered the salinity and tidal regime, as subsequently vegetation, water quality and ecology. The weir, installed in the 1980s to decrease tidal flow, collapsed shortly after installation.

Chapter 4. Sediment Cores and Diatom Analysis

This chapter presents the results of sediment cores extracted from Pattimore's Lagoon in order to investigate the long term historic evolution of Pattimore's Lagoon. The evolution of the lagoon since it became in isolated lagoonal system is also examined in greater detail using diatom fossils to model salinity changes.

4.1 Methods

Five cores of unconsolidated sediment were extracted from Pattimore's Lagoon using a mechanically operated vibracorer on 17 May 2012, (Figure 4.1). The cores were spaced in attempt to effectively cover the extent of the lagoon. Locations included; the sand delta near the channel entrance, the entrance of the original channel, the far sand-sheet in the south west corner, and two within the muddy channel in the center of the Lagoon (Figure 4.1). Cores, which ranged from 0.3 m to 2.2 m in length, were opened and visually logged following the standard procedure within the Australian Soils and Land Survey Field Handbook, 2nd edition (McDonalds et al., 1998). The cores were adjusted for compaction by comparing both measured core penetration vs. recovered depth. The cores were not leveled to the Australian Height Datum (AHD).

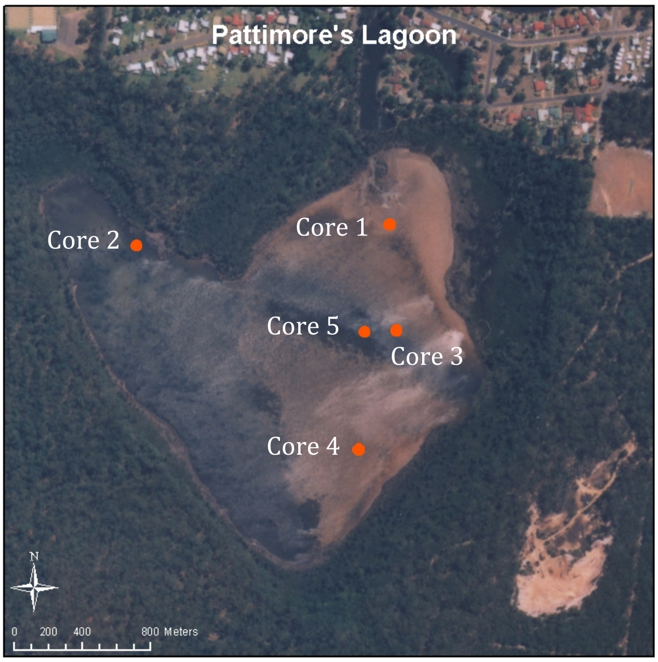


Figure 4.1: Core Locations across Pattimore's Lagoon.

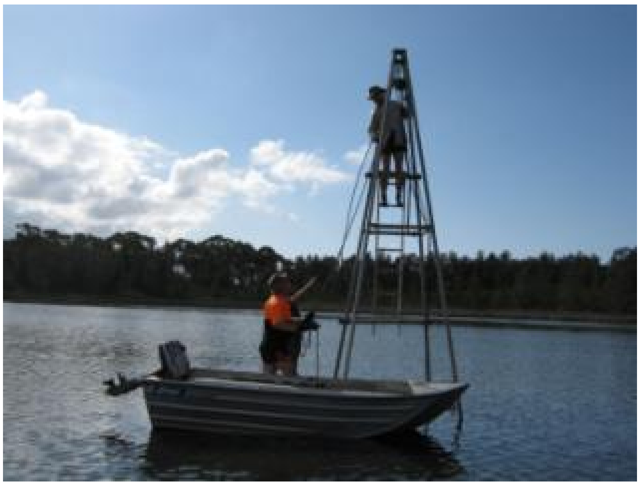


Figure 4.2: Vibracoring in Pattimore's Lagoon on 17 May 2012. Present in photo is Brian Jones, Brent Peterson, and Sam Marx. Photo taken by Ashlee Clarke.

After cores were visually analysed and logged sediment colour was logged using a Munsell Colour Chart. Ten samples were taken along Core 2. The organic content of the samples was measured, as well as sediment size grain distribution. Amino Acid Racemisation (AAR)dating was used to date the core and find average rate of sedimentation. Lastly, a diatom analysis was run top 60 cm of Core 2 in attempt to model the salinity levels in the lagoon since its isolation from Lake Conjola. The log of cores 1-4 can be seen in Appendix 1.

Sediment size was analysed using a Malvern Mastersizer 2000. A Malvern Mastersizer 2000 measures particles size through laser diffraction. To do this the intensity of light scattered by the particles as they pass over the laser beam is used to calculate the size of the particles (Malvern Instruments Ltd, 2012).

The organic matter content was determined using a Loss on Ignition test. Samples were dried in an oven over night to remove all moisture and weighed. The samples were then incinerated at 400 °C for approximately 20 hours, cooled in a desiccator and weighed again. This difference in weight was taken to represent the lost organic matter, giving the organic matter content of each sample.

Five Shell fossils, *Batillaria australis* found within the cores 1 and 3 were dated using Amino Acid Racemisation (AAR) dating. AAR is a useful geochronological tool which can be used to date fossils preserved in sedimentary successions spanning from early Holocene to recent (Sloss et al., 2010). All living things are made of proteins, which are made up of amino acids. The majority of living things use L-amino acids, but after death, L-amino acids spontaneously convert to D-amino acids, in a process called racemisation. The degree of racemisation is partly a function of time. AAR dating uses the ratio L-form and D-form to indicate how long the fossil has been dead (Pitman, 2004). However, the rate of racemisation is reliant on a variety of environment factors, including but not limited to, temperature, amino acid composition of protein, water concentration, and pH. To use AAR dating the dating must first be calibrated to other techniques such as Carbon 14 dating (Pitman, 2004).

In this thesis, the AAR dating used calibrations previously developed for Lake Conjola from Sloss et al (2010). The average amino acid D/L ratios were found for each sample by using at least three-replicated injection on a reverse-phase high performance liquid chromatograph at the University of Wollongong laboratories. The D/L ratios can be seen in Appendix 2.

The dates found were used to calculate the average sedimentation rate within the samples, assuming a stable sedimentation rate. However, due to sediment compression, cores dates often show an exponential relationship, with older dates showing more compressed, than younger dates, thus showing a faster sedimentation rate than more recent sediments. Within this thesis, only older dates were found, and so a linear relationship for dating had to be assumed.

Core 2 was chosen to complete the diatom analysis because this core was in the far west corner of the lagoon, which would be the last area to dry up in the case of extreme droughts. It was also the furthest from the new channel entrance, and thus, would be the least effected by sedimentation from Lake Conjola, which could interfere with results. Four samples were extracted within the top 60 cm of Core 2, representing the lagoonal period Ideally, more samples would have been run, but time restriction did not allow this. Further investigation of diatoms would be needed before a clear and representative salinity pattern for Pattimore's Lagoon could be found.

Diatoms are unicellular, eukaryotic organisms classified as algae. They have siliceous cell walls with intricate patterns that allow most individual species to be identified. Diatoms species often have distinct ecological requirements, and are highly sensitive to changes in water quality. Due to this, they can be used to indicate environmental change or model past environments. In this study they were used to indicate the historic salinity regimes (BATIARBEE *et al.*, 2001, Saunders, 2011).

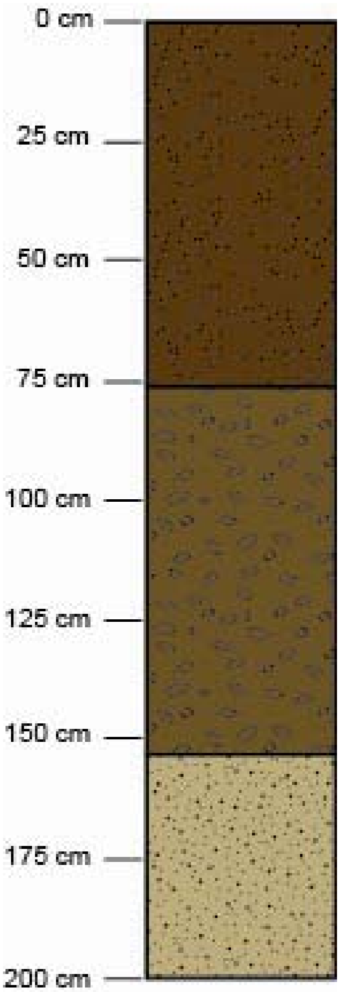
To prepare samples for diatom analysis a standard procedure was followed (BATIARBEE, 1986, Renberg, 1990) . Sample preparation involved twice simmering samples in hydrochloric acid twice and then twice in hydrogen peroxide. All samples were settled for 12 hours and decanted carefully to avoid losing any diatoms. Slides were prepared using Naprax and inspected under a microscope. Individual species identified and counted to produce a representation of the specific environment at that point in time.

Diatom species and salinity tolerances were identified using a variety of sources, (Bennion *et al.*, 2002, Bortone, 2004, Fluin *et al.*, 2009, Guadalupe-Oliva *et al.*, 2008, Guiry and Guiry, 2012, Hasle and Lange, 1989, Pappas, 2002, Spaulding, 2009, Zong, 1997). Diatom identification was then verified through personal communication with Deborah Haynes and John Tibby from the University of Adelaide.

4.2 Results

4.2.1 Long Cores

Cores 1, 3 and 4 were long cores over 200 cm. These cores where used to model the Palaeo-evolution of Pattimore's Lagoon. Figure 4.3 depicts the generalised stratigraphic log of these cores. The AAR dating of shells was used to determine the ages of the various stratigraphic units. The shell found at a depth of 68 cm was assumed to be displaced higher in the core than originally deposited and was not used for analysis. Using the lower four dates an average sedimentation rate of 0.022 cm / year was found (Figure 4.4), while dates can be seen in Table 4.1.



Unit 1: Muddy/sandy sediment with no shells and high level of organic matter. Followed by interbedded muddy and sandy section, and then a grayish silt/sand unit. The AAR dated this unit at around 3600 ± 300 years ago.
Unit 2: Sandy/muddy unit full of estuarine shells species. AAR dating found that at 127 cm was deposited around 5900 ± 700 years ago and 135 cm dated 6200 ± 1900 years ago.
Unit 3: From 155 cm downwards clean large grained marine sand was seen. This layer dated at 7900± 1200 years ago at 189 cm depth.

Figure 4.3: Core 1 generalised stratigraphic log

Table 4.1: Amino Acid Racemisation derived ages obtained from fossil *Batillaria australis* collected from Pattimore's lagoon.

Cores	Species	Sample depth	Facies	Laboratory code	AAR age
1	*Batillaria australis*	68 cm	Lagoonal	9853a1 9853a2	5597 ± 38
1	*Batillaria australis*	78 cm	Estuarine	9853b1 9853b2	3792 ± 273
3	*Batillaria australis*	127 cm	Estuarine	9853c1 9853c2	5913 ± 711
1	*Batillaria australis*	135 cm	Estuarine	9853d1 9853d2	6169 ± 1899
3	*Batillaria australis*	189 cm	Marine	9853 e1 9853 e2	7896 ± 1192

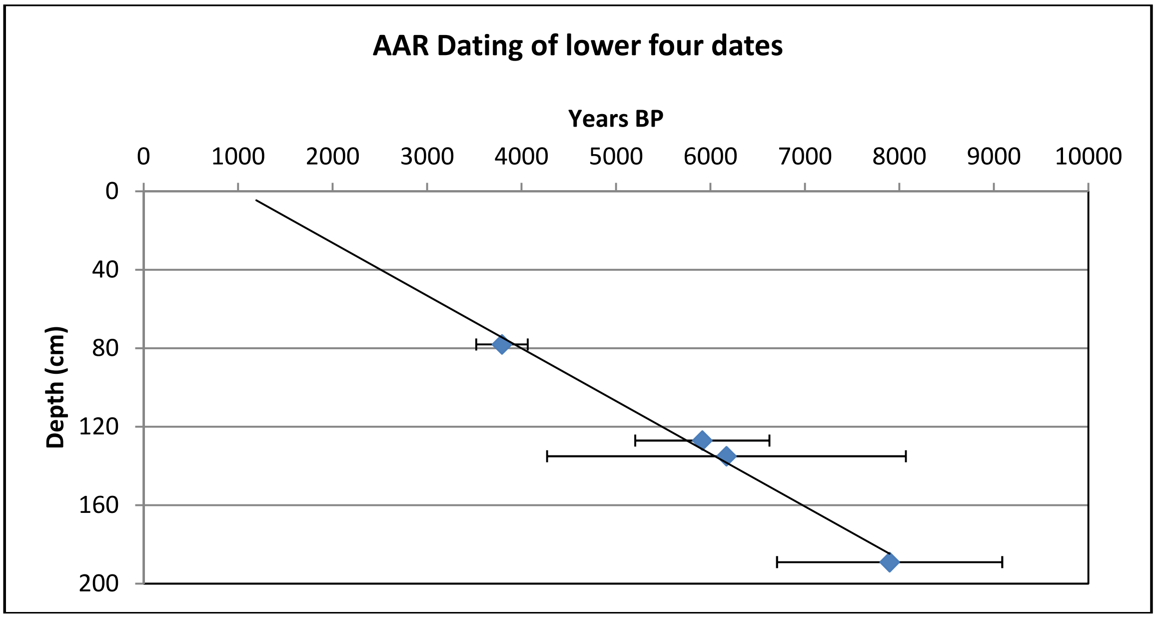
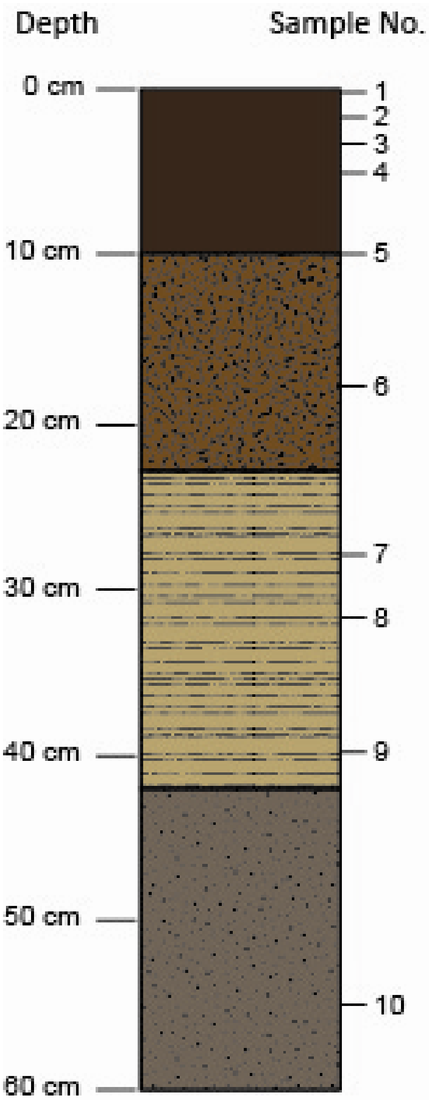


Figure 4.4: AAR dating of Batillaria australis. Dates found an average linear sedimentation rate of 022 cm/year.

The sediment profile in the long cores support the evolutionary model proposed by Sloss et al. (2010). In this model evolution began with post glacial sea level rise during the Holocene. As sea levels rose the existing Conjola river valley would have been flooded creating an open bay system. During this time, the marine sand layer seen at the base of the cores would have been deposited. Next, as sea level stabilized, in the late Holocene, a barrier system would have built at the entrance bay, changing the system from a wave dominated near shore estuary system to a sheltered back barrier estuary from ~6500 years BP. Around 3600 years ago Pattimore's Lagoon would have been created as an isolated back barrier system. (Sloss et al., 2010).

4.2.2 Short cores

The analysis of the lagoonal history of Pattimore's Lagoon focused on salinity regimes seen over the last ~3600 years since Pattimore's lagoon became an isolated lagoon system. This investigation has been taken on Core 2 and consists of Unit 1 described above. This unit consists of 4 subunits with different energy levels and levels of variability. Using the average sedimentation rate of 0.022 cm/yr found with the AAR dating, this Core 2 would be ~2700 years old, well after the lagoon was seen to become an isolated system in the long cores. The core, contains four distinctive sedimentary units (Figure 4.5) described below. The position of the samples taken for analysis can also be seen in Figure 4.5, and the organic content and grains size distribution for each sample can be seen in Figures 4.6 and 4.7 respectively.



Subunit 1 from 0-9 cm is a highly organic layer with a large amount of bioturbation. This unit was silt dominated. Approximate age from the average sedimentation rate is 500 years BP
Subunit 2, 10 cm to 22 cm, is less organic and less silt dominated layer with approximately 50% sands. This unit contains a high level of bioturbation. Approximate basal age is 1000 yrs BP.
Subunit 3, 23 cm to 41 cm, was dominated by interbedded sand and silt layers presented throughout. High levels of organic mixing, bioturbation and some small wood pieces, present. Basal ages was approximately 1900 yrs BP.
Subunit 4 for started at 43 cm, silt dominated grey coloured and less organic than previous units. Approximate basal age has this layer at ending around 1900 years BP.

Figure 4.5: Core 2 stratigraphic log and sample locations.

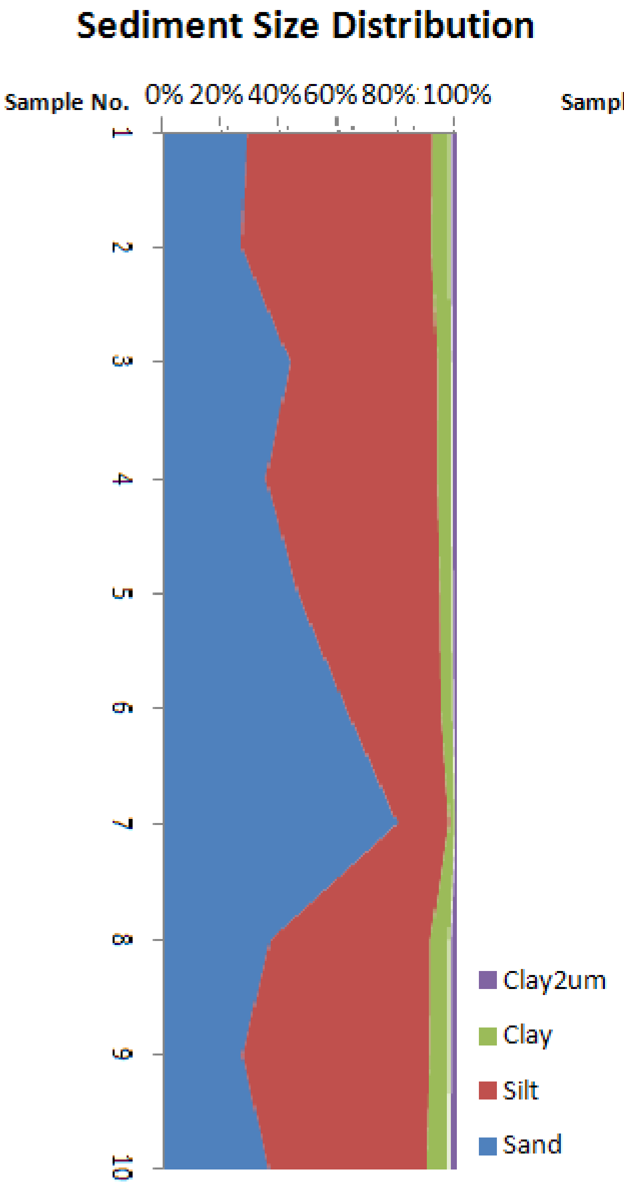


Figure 4.6: Sediment size distributions from Core 2.

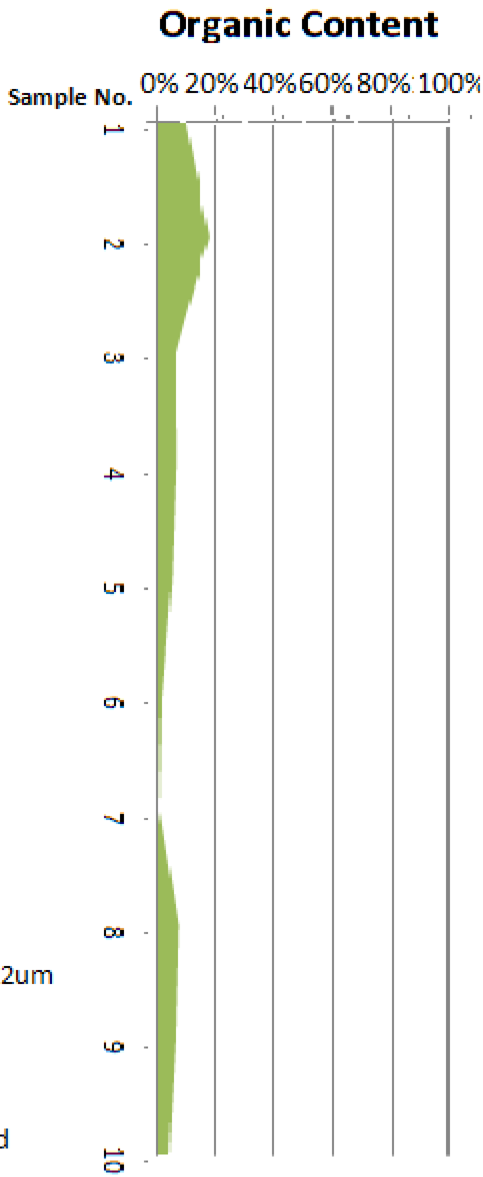


Figure 4.7: Organic content of Core 2.

The first, subunit 4, from roughly 2700 years ago to around 2000 years ago shows a period of silt and sand deposition, with little bioturbation and only ~4% organic matter. This is believed to represent the period when Pattimore's Lagoon first began functioning as an isolated system.

Subunit 3 shows a succession of sands and silt layers. Samples 7 and 9 layers consisting of over 80% sand and under 25% sand respectively. This unit also shows high amounts of bioturbation. The organic content in these layers vary from 7% organic matter to under 1% organic matter. This period, from ~200 years ago to ~1000 years ago would have been a highly variable environment in Pattimore's Lagoon.

Subunit 2, from ~1000 to around 500 years ago, consisted of loamy sand layer with high levels of bioturbation. This layer was more uniform, indicating consistent processes, but low organic levels, ~1.5% were seen. Subunit 1, representing the last 500 years, was observed to be a highly organic layer, with organic contributing up to 18% of the sediment. This layer was very dark in colour, silt dominated, and high levels of bioturbation. This would indicate that is was the most ecologically productive period

Diatoms were extracted from Sample 1, 6, 7, and 10 of Core 2 to investigate the different salinity regimes. Each sample was roughly 1 cm in length and would represent about 100-50 years according to the average sedimentation rates. Within each sample, multiple salinity environments may have been experienced. So diatoms found may represent the average conditions or extreme events experienced within the period. The type of diatoms found in each sample can be seen in Figure 4.8.

Subunit 4 was dominated by polyhalobous, or marine diatoms, with some euryhaline, diatoms which have wide ranging salinity tolerances. This was also seen in Subunit 3. This would indicate that before around 1000 years ago, Pattimore's Lagoon was dominated by a marine or high salinity system. Sample 6 from Subunit 2 indicates a system also dominated by marine and euryhaline diatoms, but diatoms which survive in freshwater, fresh to brackish water and brackish to marine water also begin to appear. This would suggest that this period is showing a general freshening of the lagoon, or a more variable environment which brackish and freshwater salinity regimes are occasionally present.

The last sample taken from Sub unit 1 represent the last ~100-50 years, since the start of the canal estate. In this sample we observed a highly variable system. The diatoms seen were primarily fresh to brackish diatoms, followed by brackish diatoms. However, fresh, brackish to marine, marine, marine to hypersaline, and euryhaline diatoms were also present. This would indicate that the modern lagoon, since the canal estate increased connection, is the most widely variable environment seen. It was also noted, that almost all of the freshwater diatoms present in Sample 1 are acidic loving diatoms (John Tibby, personal communication 2012). Diatom analysis can be seen in Appendix 3.

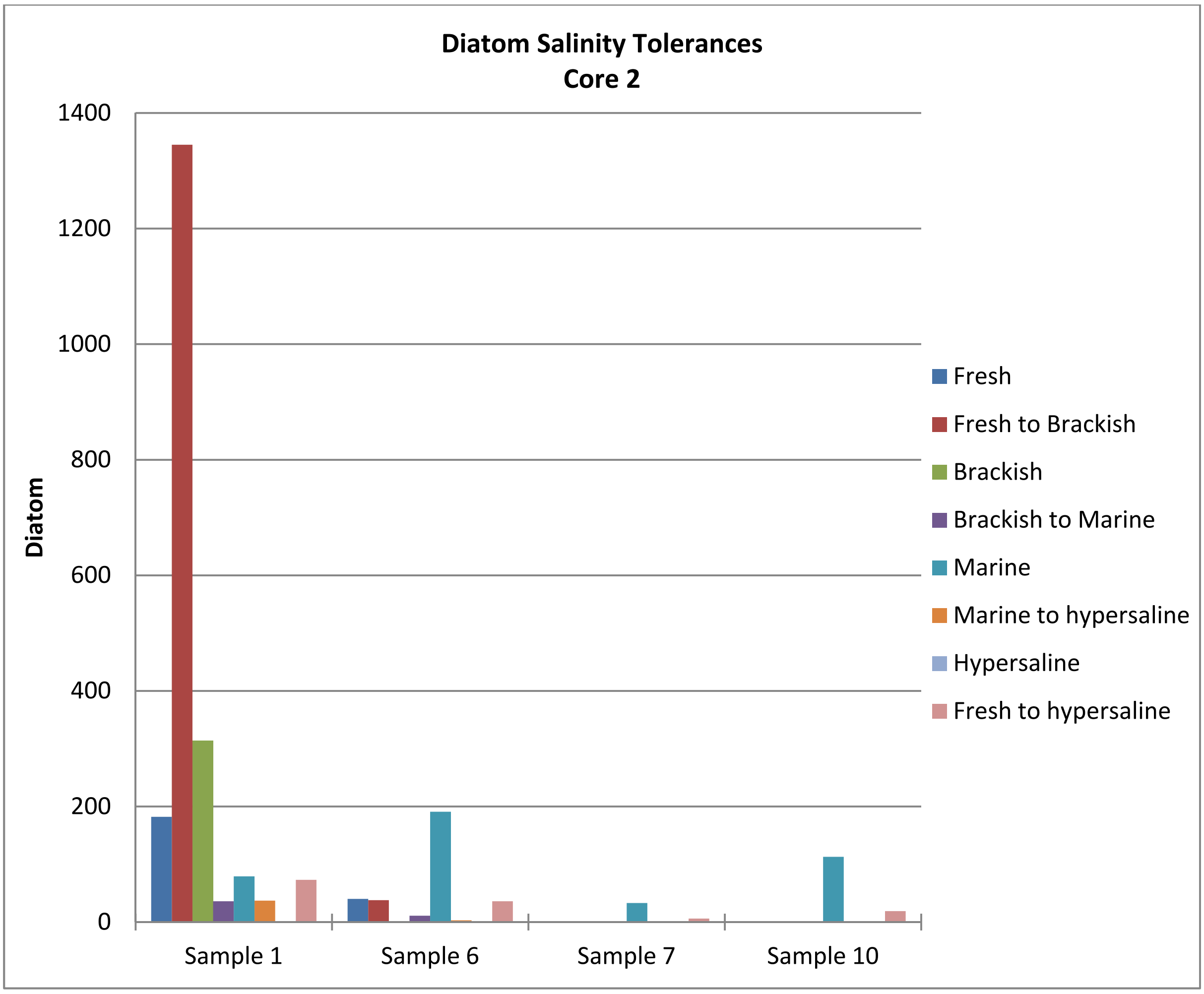


Figure 4.8: Salinity tolerances of diatoms present in each sample from Core 2.

Summary

The sediment sequences show an infilling of Pattimore's Lagoon of marine sands, followed by estuarine sediments. These sequences are followed by a more isolated lagoonal sediment, which shows variable energy levels and a steady increase in organic matter and silts, suggesting increased isolation. This sediment profile indicates that Pattimore's Lagoon has evolved as a result of sea level rise flooding a river valley and subsequently sea level stablisation leading to gradual estuary infilling, creating isolated depositional basins. Diatom analysis through the lagoonal sequence shows a system dominated by marine species from ~3500-1000 years BP. Over the last 1000 years the salinity within the system has become more variable and freshened. Presently the system appears to be dominantly brackish, but vary from fresh to hypersaline.

Chapter 5. Aerial Photograph Analysis

5.1 Methods

Changes within Pattimore's Lagoon from 1950 -2011 were mapped using aerial photographs. This period covers the events, development of the canal estate, which is believed to have significantly influenced Pattimore's Lagoon. Photographs span the time before the canal development to post canal establishment and post weir collapse. ArcGIS, a Geographical Mapping and Analysis program, was used to map quantify visible changes experienced in and around Pattimore's Lagoon over the last 60 years. Photographs were sourced from the School of Earth and Environmental Sciences Map Library and NSW Stage Government, Office of Environment and Heritage. Availability of historical photos dictated the years available for analysis and photo quality was commensurate with what was available during the various years of capture. For example, older imagery has a poorer resolution that images acquired more recently. The aerial photograph from 2011 was not used in all analysis as it did not cover all areas examined.

Aerial photographs were scanned using a digital flatbed scanner at a resolution of 900 dpi (dots per inch). This resolution was deemed the most appropriate, as it showed the most detail possible without blurring the older images. The photographs were then geo-referenced to an orthorectifed digital aerial image. Road and rail spatial data from the NSW Digital Topographic Database (as at October 2009) was used in a best-effort evaluation of the accuracy of the image georeferencing. Six data layers were created in an attempt to map the types and scales of change experienced as a direct result of the artificial canal development, the data layers created, type of layer, method of evaluation, and the reason such a layer was deemed important is outlined in Table 5.1. The metadata for spatial layers created is located in Appendix 4.

In layers with distinct patterns of change, further analysis was undertaken to model the extent and direction of change. The main analysis made modeled the delta growth rate. Time-series of other changes were also created to best show the changes observed.

Table 5.1: Data Layers

Feature	**Type of Object used**	**Method of Evaluation**	**Importance**
Canal Area	Polygons One shapefile per image	Canal edges were captured from each year of imagery.	The change in size and position of the canal estate would be expected to lead to changes in the tidal flushing and salinity of Pattimore's Lagoon
Canal Entry Point	Lines	A line marking the interface between the canal and the lagoon was derived using a visual analysis of each year of imagery	Entrance point of canal was artificially moved in the making of the canal estate.
Delta Area	Polygons One shapefile per image	The size, shape, and position of the delta were captured by outlining the delta, canals and sand deposits.	The growth of the delta could indicate sedimentation rates and tidal influence into the lagoon.
Tree-line	Lines	Lines marked interface between continuous tree cover and lower groundcover with some sparse trees.	Shift in the tree line would show change in salinity or tidal regime.
Lone tree	Points	Point was placed on each tree observed below the tree-line within the ground cover	A decrease or increase of trees in the ground cover layer could signify a change in tides or salinity. The increase in trees along the edge of the Lagoon could model growth of mangroves.
Ground Cover	Polygons	Polygons were placed around groundcover areas. In recent photographs different types of ground cover were discernable this was included in the attribute table, insufficient resolution in some imagery prevented this from being used explicitly in any analysis	Groundcover movement would represent changes in tidal regime or water level, though without species level information would not show salinity levels.

5.2 Results

Analysis of the changes within Pattimore's Lagoon from 1950 to 2011 showed distinct changes within the Lagoon. Dramatic changes occurred in the canal area and entrance location, delta, and some areas of the tree-line. While changes were observed in the number of trees present and the ground cover area, the low resolution in the older photos made it difficult to map accurately. The lagoon edge showed subtle shifts, but no significant changes. Groundcover was mapped, however variation in resolution and quality across all photographs made it difficult to compare groundcover types between years, for this reason, groundcover was not analysed further.

5.2.1 Lagoon edge

The Lagoon edge showed very little change over the time period as can be seen in Figure 5.1. It could be argued that the lagoon experienced some movement inwards on the western side, but this movement is too subtle to draw any conclusions, i.e., the change is deemed within the error associated with geo-referencing.

5.2.2 Channel

The Pattimore's-Conjola channel experienced dramatic changes from 1950 to 1999 due to the construction of the artificial canal estate and drainage canals. A time series of changes can be seen in figure 5.2. The observable

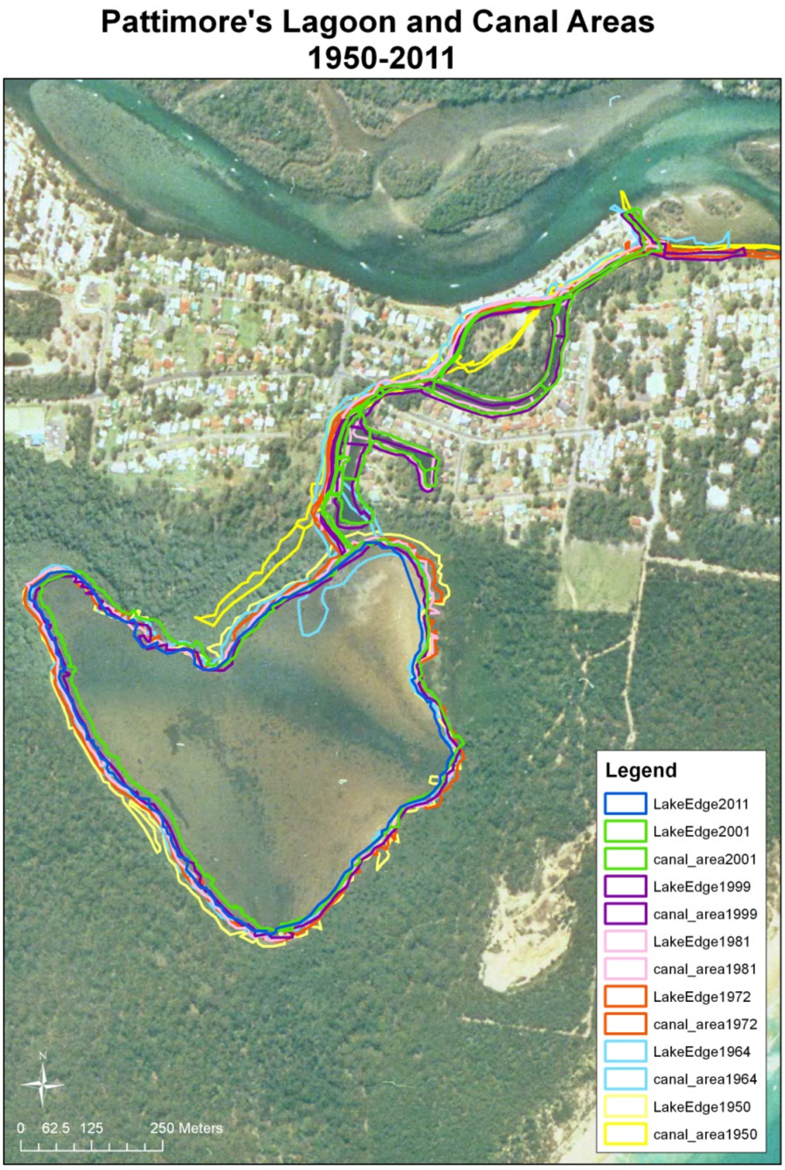


Figure 5.1: Outline of Pattimore's Lagoon and channel from 1950 to 2011.

changes in the lagoon are summarised below;

a. In 1950 the Pattimore's Lagoon appears to be connected to Lake Conjola by a small natural creek which meanders slightly and enters Pattimore's Lagoon on the northeast corner. A small delta is distinguishable where the creek enters the lagoon, though it is very small, and possibly a remanet.
b. From 1950 to 1967 two area of vegetation were cleared and at least one diverted the creek from entering the northwest edge to the northeast edge. It appears that sediment built up at the new entry point, though the extent is difficult to distingish. It also appears that the remainder of the natural channel seems to be dry and empty, and the old delta is no longer discernible. .
c. By 1972 only one of the vegetation clearances remains and a small delta can be seen the entrance of the larger channel entrance with the lagoon. The natural creek had begun to fill in and is difficult to distinguish in the photo.
d. In 1981 most of the canal estate had been constructed with the exception of the most southern section. The flow path of the system had been altered by the addition of large extra bend in the lower creek, and a dead end canal arm extension. Trees had begun to grow along the original creek line while the delta associated with the new connection to the lagoon had grown with vegetation starting to establish on deltaic sediment.
e. By 1999 the canal was fully established and a second arm was added ending very close to Pattimore's Lagoon. At this point the delta is very developed and well vegetated. At this point the delta appears to have reached its current size.
f. In 2001 the Canal estate and delta appear very similar to 1999, with more established vegetation along both. The extent of the natural channel had been effectively been filled with and the tree-line reached the water's edge. The old delta is very difficult to distinguish, as is the former natural creek line.

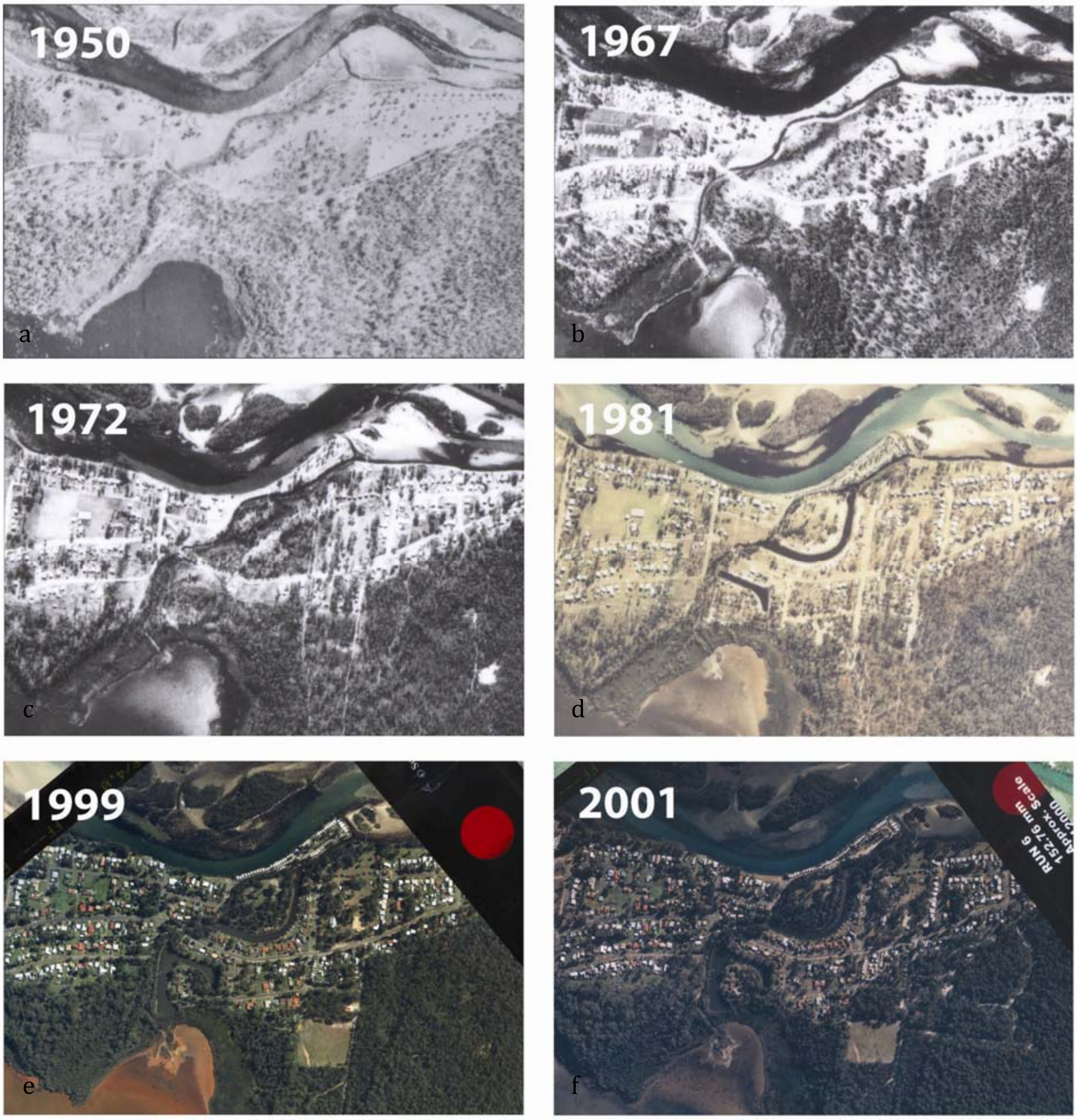


Figure 5.2: Time series of channel and canal development from 1950 to 2001.

5.2.3 Delta

One noticeable change within the lagoon is the growth of a delta in the north eastern corner of the Lagoon. This growth can be observed in the time series seen in Figure 5.3

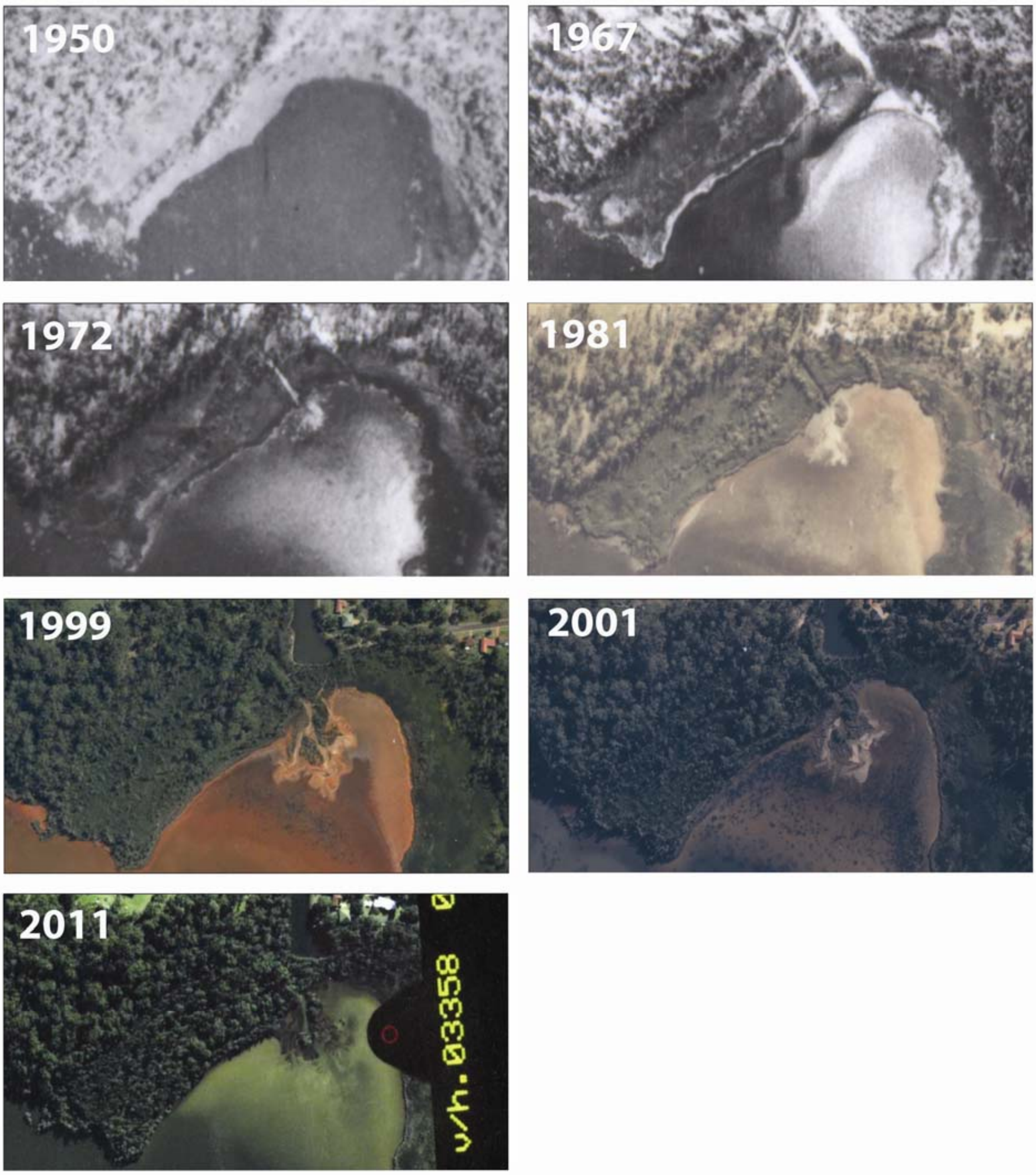


Figure 5.3: Time series of delta development in Pattimore's Lagoon from 1950 to 2011.

The growth of the delta was mapped using the extent of obvious deltaic sediment in each photograph. This is a limited examination as the start of the delta growth is not known, though it began between 1967-1972. There are also some large gaps in photographs, e.g. 1981-1999, making detailed growth rate modelling difficult. Analysis is also limited by varying water levels between images, as well as the resolution of the photographs which makes the edge of the delta difficult to ascertain.

Nevertheless, rapid delta growth can be observed from ~ 1970 to the late 1990's , during which, the delta has grown by approximately 300 m^2 yr^{-1}, as can be observed in the graph of delta growth (Figure 5.4) and visual model (Figure 5.5). After the late 1990's the delta slowed or stopped expanding, which could imply either the system has reached equilibrium, or sediment supply has decreased. An increase in vegetation extent along the delta can also be observed with vegetation on the delta first appearing in 1981 and increasing greatly until 2011. Field observations in 2012 found over 3 m tall casuarinas growing along the delta, as well as other vegetation.

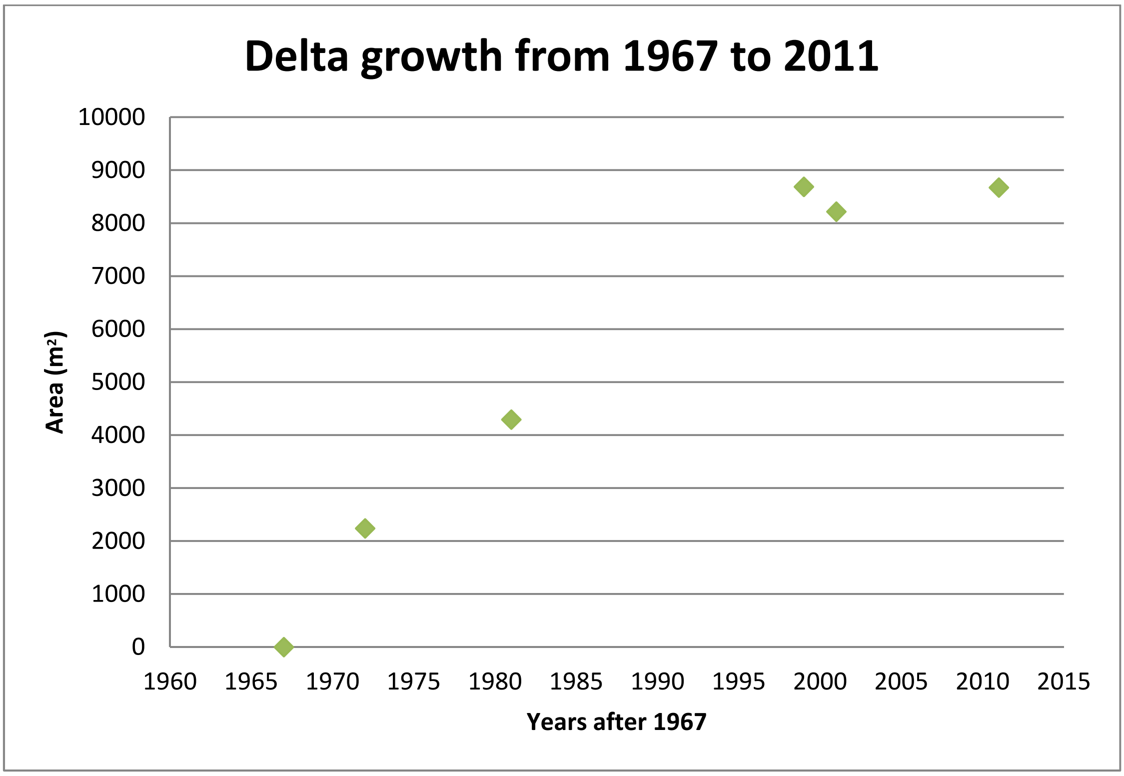


Figure 5.4: Rate of delta growth from 1967 to 2011, determined from aerial photographic mapping.

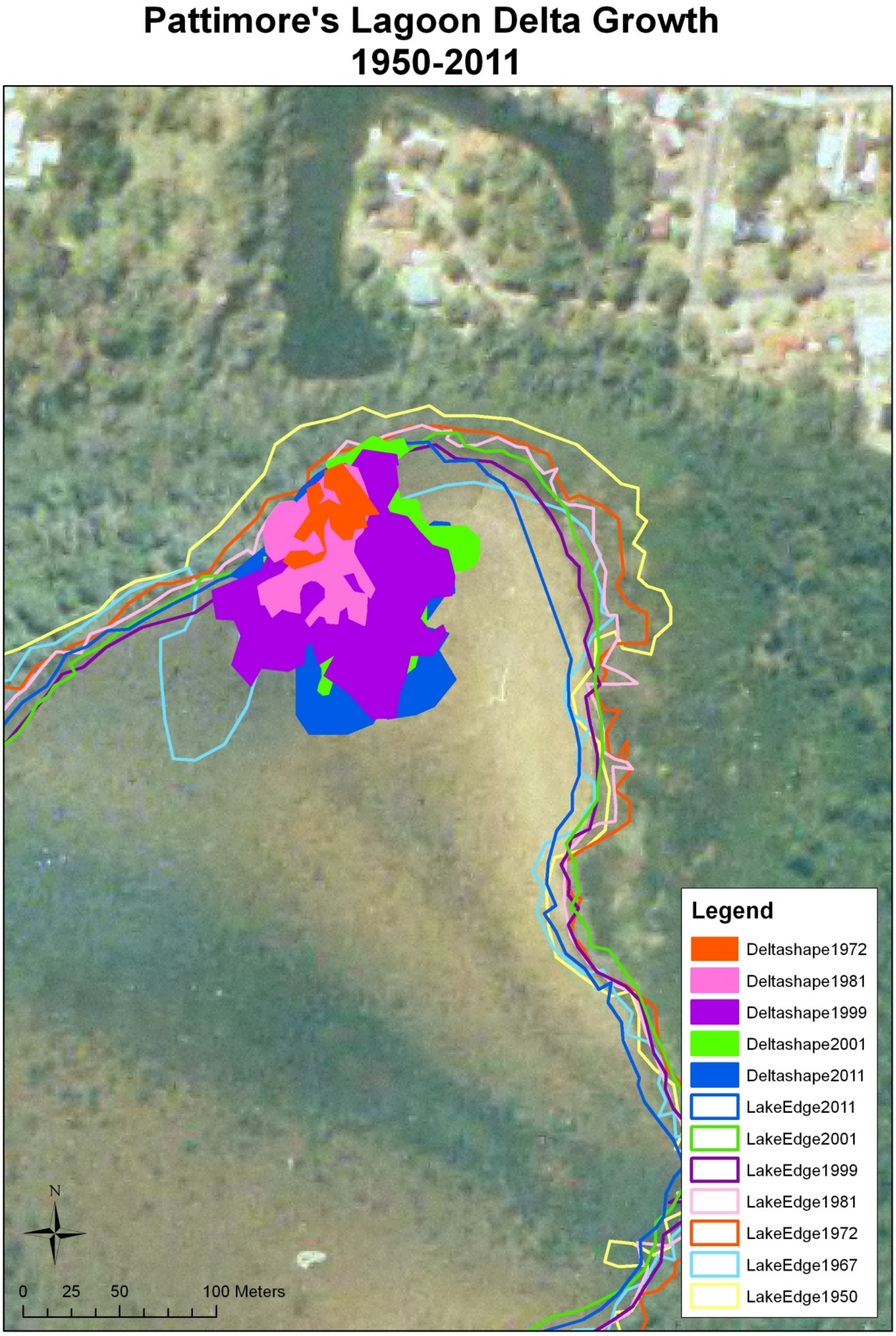


Figure 5.5: The growth of deltas from 1972 till 2011 in Pattimore's Lagoon.

5.2.4 Tree-line

A noticeable shift can be seen tree-line around the lagoon, mainly in the northern edge around the old channel entrance as can be seen in Figure 5.6. The area of the original creek can be observed to slowly infill with vegetation and trees over time until the tree-line reached the water edge by early 2000's. This infilling would be a direct result of the redirection of the channel to its new entry point.

A shift along the southwest edge can be seen as the trees gradually moved towards the lagoon edge, while along the eastern the tree-line seems to shift away from the water's edge slightly. These trends are not seen in every year, and slight variation in photographs due to difficulties with georeferencing older images could be responsible for some of the changes. However, in comparison to the Lagoon edge, there is greater movement in the treeline, showing there was some significant movement in these areas, though exact trends are difficult to discern.

It can be seen in 5.6 that the treeline in 2011 on the eastern edge of the lagoon veers towards the water's edge dramatically. The 2011 image was taken with Pattimore's lagoon on the very edge, and cut out the far northeast corner of the lagoon. As such any distortions on this side was difficult to account for, and exact georeferencing difficult. Due to this, this image was not used for further analysis.

5.2.5 Lone-trees

The analysis of lone tree extent showed some significant changes following the trends seen in the tree-line analysis. In older images with low resolution, lone tree's were much harder to distinguish, and it can be assumed that many which would have been picked up in more recent images may not have been discernable in the older images, this analysis should be viewed with skepticism and only used in conjunction with the tree line. An increase in trees around the old channel and infilling of trees along the eastern and western edges of the lagoon were observed. This agrees with the observations of the treeline and it may be assumed that these are responding to the same factors.

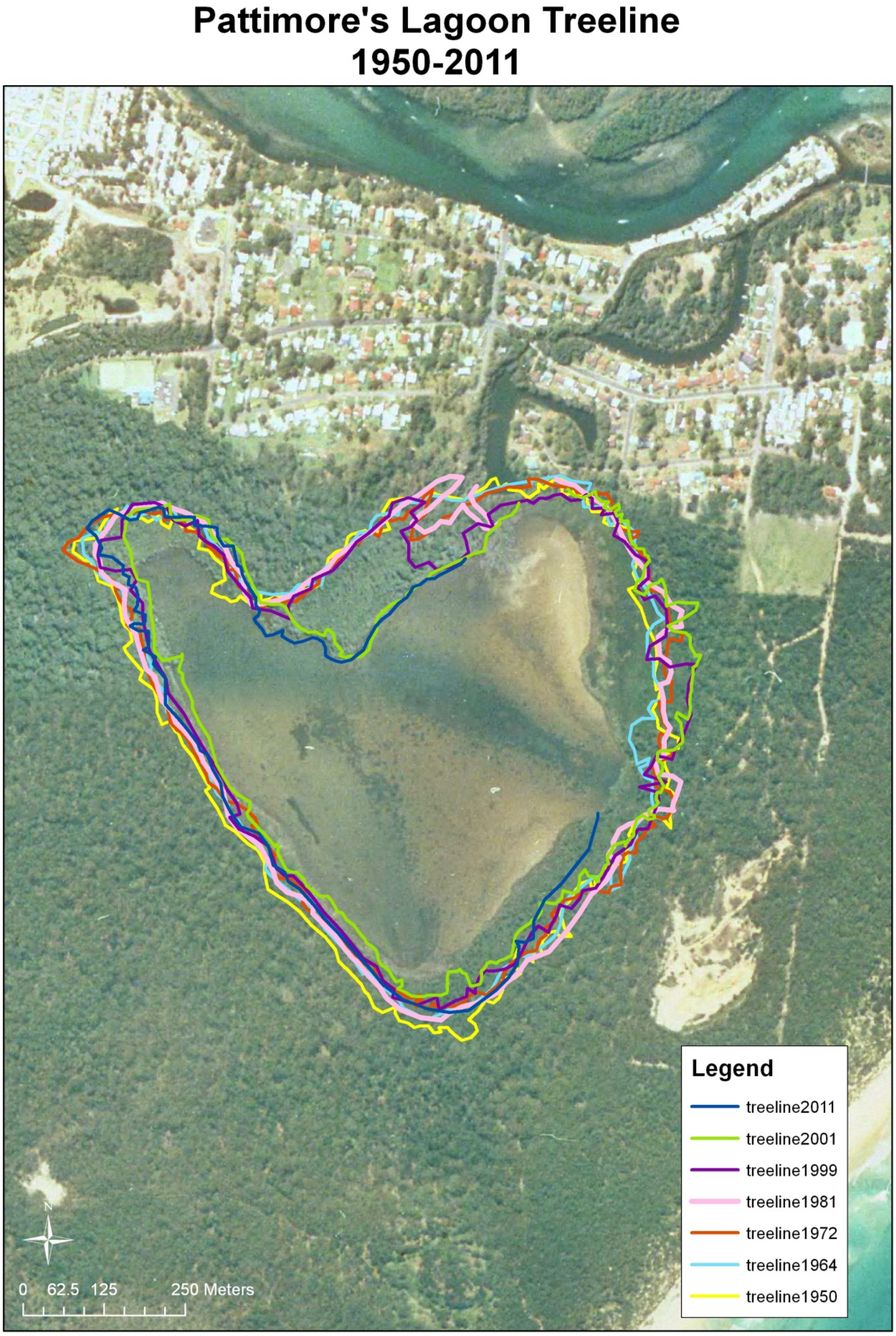


Figure 5.6: The treeline around Pattimore's Lagoon from 1950 to 2011.

Summary

This analysis has proven that the canal estate has resulted in changes within Pattimore's Lagoon. The increased channel area has led to the rapid deposition of sediment into Pattimore's Lagoon creating a delta at the new channel entry point. The original channel did have a small delta, but the much larger delta which has built in the last 50 years shows that there was a significant increase in tidal flow reaching Pattimore's Lagoon. Other changes, such as shifts in treeline are also believed to be a direct result of the canal estate.

Chapter 6. Tidal regimes

This chapter examines the current tidal environment of Pattimore's Lagoon. It is believed that the tidal regime within Pattimore's Lagoon has been one of the major factors influenced by the development of the canal estate. To address this, Chapter 6 first examines the tidal environment of Lake Conjola and its influence on Pattimore's Lagoon. As an ICOLL, Lake Conjola's tidal regime is highly dependent upon entrance conditions, and experiences a range of tidal environments under different levels of entrance shoaling. Next tidal planes within Lake Conjola are examined with specific attention to the level of tidal attenuation experienced in Pattimore's Lagoon. With this, the effectiveness of the degraded weir at preventing tidal penetration into Pattimore's Lagoon is assed under different tidal conditions. Lastly the effects of the entrance conditions and water levels on the salinity within Pattimore's Lagoon are briefly discussed.

6.1 Methods

Figure 6.1: Sensus Ultra dive recorder secured to a brink before being placed in Pattimore's Lagoon for 3 months.

To measure the tidal signal with Pattimore's Lagoon above the weir and within the channel downstream of the weir, ReefNet inc. Sensus Ultra dive recorders installed from 26/03/12 to 31/07/2012. One recorder can be seen in Figure 6.1, tied to a brink before being sunk in the lagoon. ReefNet Ultra dive recorders record depth with a resolution better than 1-2 cm and an accuracy of ± 30 cm (ReefNet Inc., 2012). The ReefNet recorders are non-vented and therefore require a correction for variability in atmospheric pressure. This was accounted for by installing a third recorder within a tree beside Pattimore's Lagoon during the sampling period. Atmospheric variation was then corrected by subtracting the atmospheric pressure trace from the tidal trace. Additional data for 2008-2009 from Pattimore's Lagoon was obtained from the Manly Hydraulics Laboratory. This data was collected during a data collection exercise undertaken in Lake Conjola for estuary management. This data was collected using a Aquistar PT2X pressure sensors temporary installed in Pattimore's Lagoon (Manly Hydraulics Laboratory, 2009). Similarly Lake Conjola entrance data from 2007-2012 was also supplied by Manly Hydraulics Laboratory, collected by a permanent water level recorder at Lake Conjola's entrance channel. The location of these gauges can be seen in Figure 6.2.

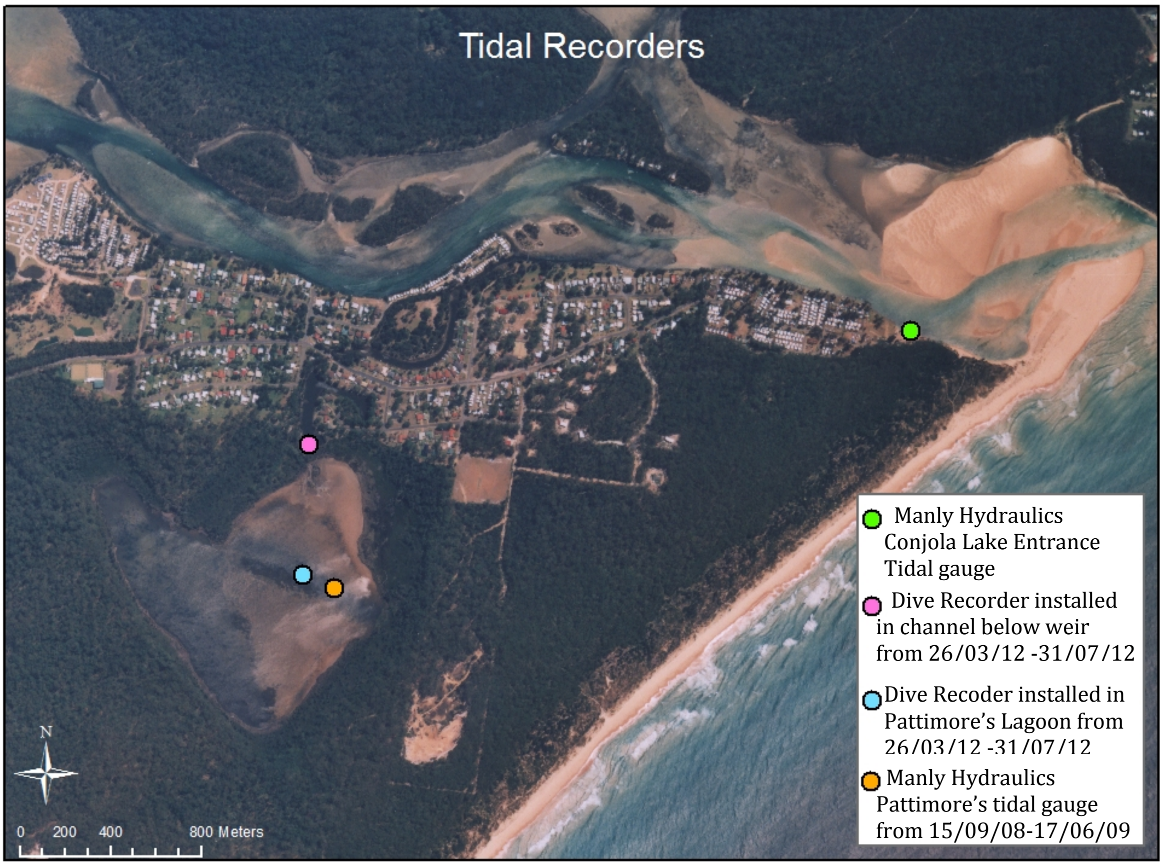


Figure 6.2: Tide recorders in Lake Conjola and Pattimore's Lagoon. Two recorders were installed by Manly Hydraulics Laboratory and two during the course of this research (Manly Hydraulics Laboratory, 2009).

Lake Conjola's tidal regime was examined through the M2 tidal Constituent, the principal lunar semidiurnal constituent which results from the rotation of the Earth with respect to the Moon with all other environmental factors removed. The M2 tidal Constituent has been recorded by Manly Hydraulics since 1993 and tidal data from Lake Conjola's entrance tidal gauge (Manly Hydraulics Laboratory et al., 2012) This analysis compares the level of entrance shoaling to that of the diurnal tide and. spring tide pumping signal.

Tidal attenuation was modeled by finding the average difference in high water spring tides, low water spring tides, high water neap tides, and low water neap tides recorded between the open ocean, Lake Conjola entrance, the channel, and Pattimore's Lagoon for the month of April 2012.

The effectiveness of the weir was examined by comparing the tidal signal seen within the channel downstream of the weir to that seen within Pattimore's Lagoon above the weir.

The effect of the tides on salinity was examined by comparing salinity within Pattimore's Lagoon to the M2 constituent and water levels seen in Lake Conjola throughout that period.

Preferably salinity data would also be compared to rainfall patterns and ocean wave conditions but further analysis was not possible due to time restrictions.

6.2 Results

6.2.1 Lake Conjola's Tides

The M2 tidal constituent is the principal lunar semidiurnal constituent which results from the rotation of the Earth with respect to the Moon with all other environmental factors removed (Manly Hydraulics Laboratory, 2012). Lake Conjola's M2 tidal constituent has been recorded for Lake Conjola for almost 20 years. This recorded has been used to model the level of Lake Conjola's entrance shoaling, and signal when the entrance as reached the level of shoaling at which lake entrance closure is imminent (Manly Hydraulics Laboratory et al., 2012). During the 20 years of monitoring Lake Conjola's entrance condition, and thus the effective M2 tidal constituent within the lake, have varied greatly. Lake Conjola entrance has been gradually shoaling for the last 5 years and has shut periodically in the last 2 years in spite of attempts to open the entrance. The M2 constituent during the different periods of tidal records used in this study can be seen in Figure 6.3.

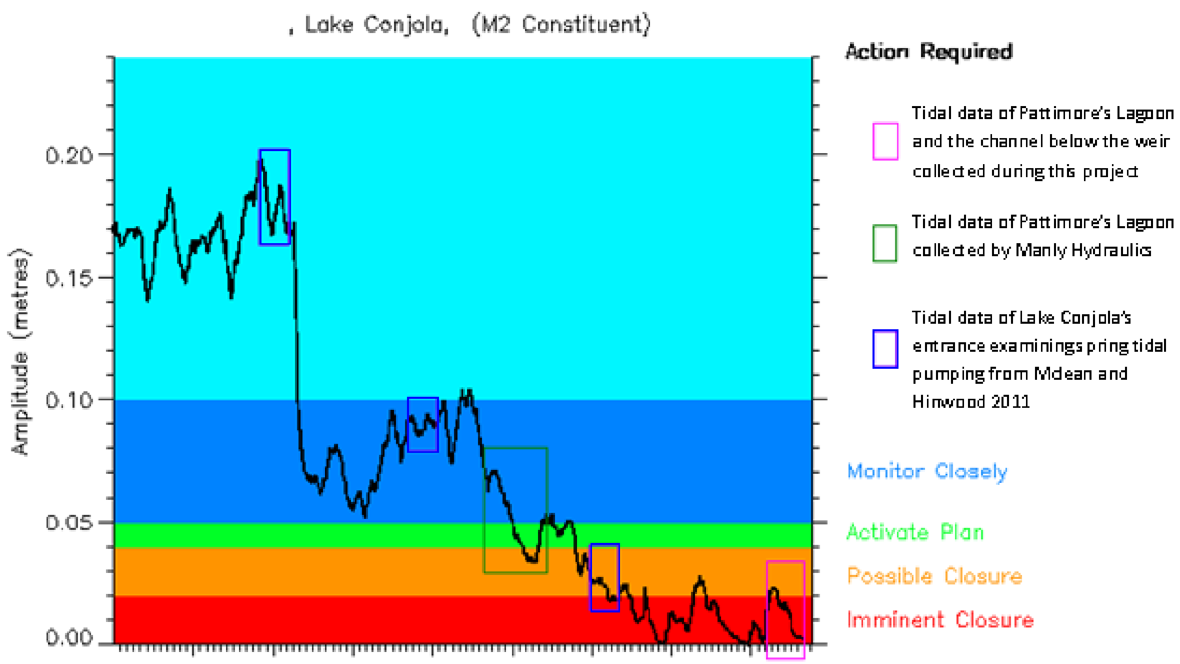


Figure 6.3: M2 tidal constituent in Lake Conjola from 1993 to 2012 used in a decision support system to monitor Lake Conjola's entrance shoaling. This system signals when the entrance is nearly closed. Diagram modified from Manly Hydraulics et al. 2012.

The two periods of tidal data from Pattimore's Lagoon where collected during different M2 tidal constituents within Lake Conjola (Figure 6.3), this indicates different degrees of entrance shoaling. During the 2008-2009, Lake Conjola's M2 constituent showed a tidal range of 0.07m and 0.035m, while in 2012, the M2 tidal range was only 0.025m to 0.005m.

Spring Tidal Pumping

Spring tidal pumping is the caused by tidal forcing during spring tides which results in an increase in mean water level in estuaries. Spring tidal pumping operates over 14 day spring tide cycles. Spring tidal pumping occurs when spring tides flow into estuaries, but do not fully drain out, gradually increasing water levels. During neap tides, the water is able to drain back out returning water levels to normal heights. Often this phenomenon increases with the level of entrance restriction.

This process is often important in estuaries with constricted entrances and can result in estuary flushing and wetland inundation (McLean and Hindwood, 2011). It has previously been demonstrated that as Lake Conjola's entrance restricts, spring tidal pumping becomes increasingly prevalent (McLean and Hindwood, 2011). Figures 6.4, 6.5 and 6.6, show that the tidal signal in Lake Conjola's when entrance of Lake Conjola open, partially shoaled, and nearing closure, respectively These figures show that as the entrance is constricted the tidal cycle changes from dominated by a diurnal tidal cycle to one dominated by a 14 day spring tidal pumping cycle (McLean and Hindwood, 2011) .

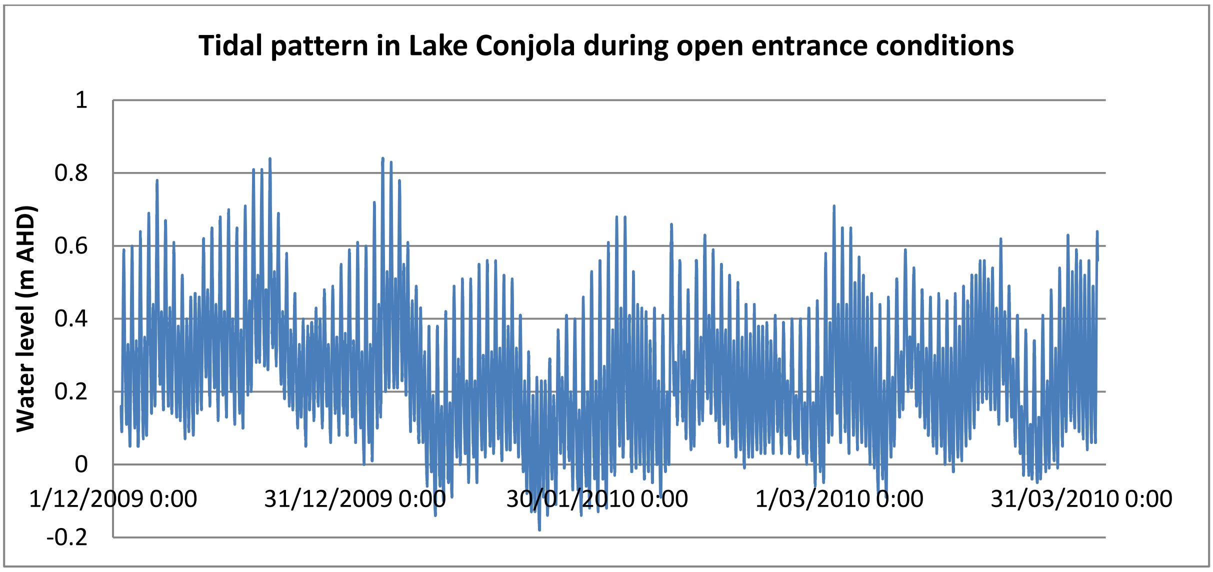


Figure 6.4: This figure shows the water level variation from November 2005-March 2006 when the entrance of Lake Conjola was open and M2 tidal constituent was at 0.16 m-0.20 m, as shown in Figure 6.3. This graph shows strong diurnal tidal signal, as expected during open entrance conditions.

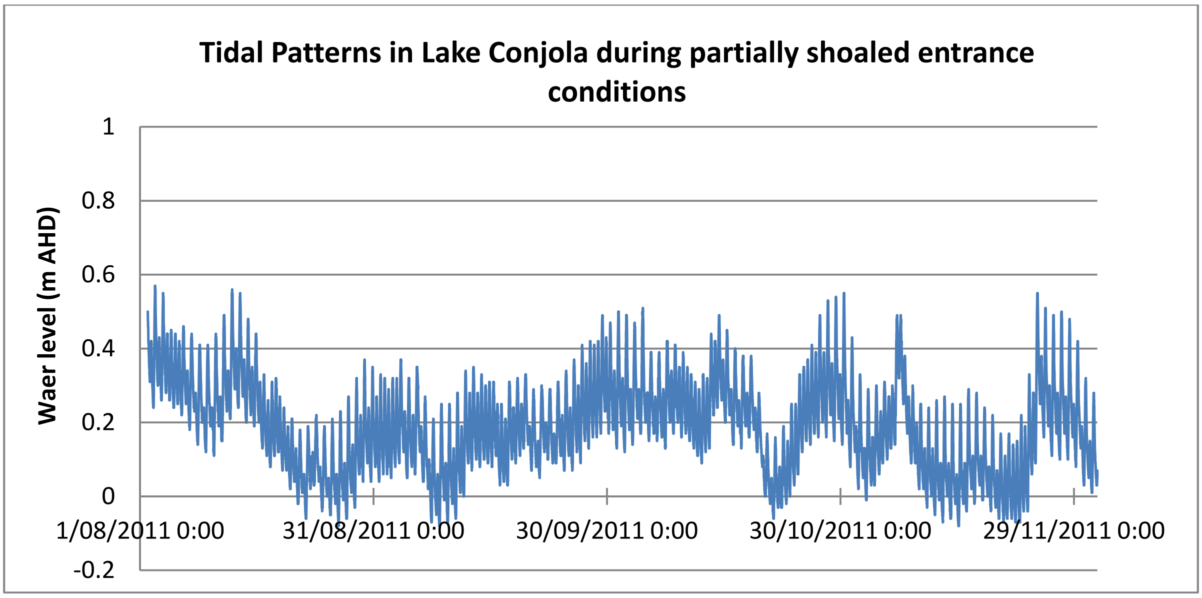


Figure 6.5: This figure shows the water level variation from July -November 2007 when the entrance of Lake Conjola was partially shoaled and M2 tidal constituent was at 0.08 m-0.09 m, as shown in Figure 6.3. This graph shows a reduced diurnal tidal signal with a underlying pattern of spring tidal pumping, as expected during partially shoaled entrance conditions.

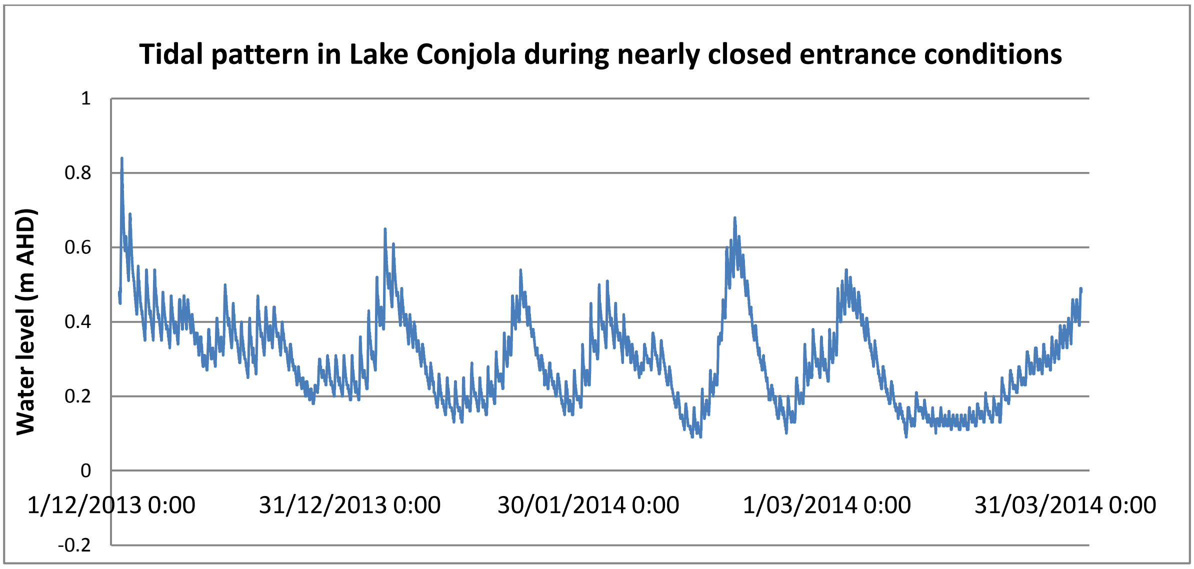


Figure 6.6: This figure shows the water level variation from November 2009 – March 2010 when the entrance of Lake Conjola was nearing closure and M2 tidal constituent was at 0.02 m-0.03 m, as shown in Figure 6.3. This graph shows spring tidal pumping cycle with a very reduced diurnal tidal signal over the top, as expected during nearly closed entrance conditions.

The average daily water level during each of the entrance condition was found by creating a 24 hour running mean to cancel out the diurnal tidal cycle. It can be observed during the open entrance conditions seen December 2005- March 2006 water levels varied from 0.49 m AHD to 0.01 m AHD, and the overall average daily water level was 0.25 m AHD. From August-November 2007, during partially shoaled entrance conditions, daily average water levels varied from 0.38 m AHD to 0.2 m AHD and the average water level throughout the period was 0.18 m AHD. From December 2009-March 2010, during nearly closed entrance conditions, daily average water levels varied from 0.64 m AHD to 0.12 m AHD, and the overall average for the period was 0.30 m AHD.

From September 2008 to June 2009, water levels in Lake Conjola varied from 1.0 m AHD to 0 m AHD, while Pattimore's Lagoon varied from 0.16 m AHD to 0.63 m AHD. Throughout this period the entrance was partially shoaled, and it was assumed spring tidal pumping was influencing water level fluctuations. It was seen that during 2008, when the entrance was in a partially shoaling state, the 14 day cycle occurred alongside the diurnal tidal pattern (Figure 6.5). In 2009, as the entrance continued to shoal, spring tidal pumping signal increased while the diurnal tidal single decreased (Figure 6.6)

From March to July 2012, Lake Conjola entrance was near closure and thus spring tidal pumping was expected to be one of the major factors responsible for water level variation seen in Pattimore's Lagoon during this period. The data from Pattimore's Lagoon and Lake Conjola from 2012 show spring tidal pumping was a more important factor than diurnal tidal signals, though others other factors can be seen to influence water level, such as rainfall and ocean wave spill over. Ocean wave spill over is the occurrence of large waves washing over the entrance berm and into Lake Conjola, increasing water levels. It can be seen in Figure 6.7-6.9 that some peaks correlate to 14 day spring tide pumping, while others can be seen to result from rainfall. Some of the peaks, or reduced troughs, do not correlate with rainfall or spring tide pumping, and in these cases it is assumed that they correlate to wave spill over. It can also be noted that it appears that Pattimore's Lagoon experiences a larger tidal signal in 2012 than in the other periods examined.

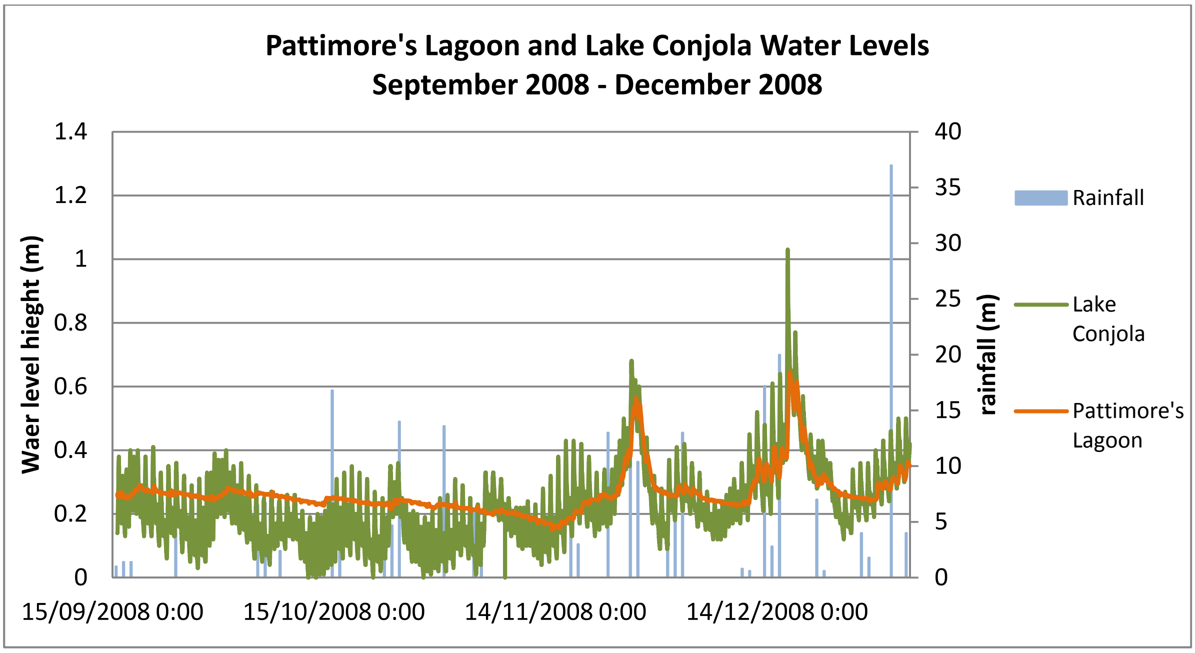


Figure 6.7: Water level variation from September to December 2008. This graph shows the tidal pattern recorded at Lake Conjola entrance and Pattimore's Lagoon during shoaled entrance conditions. A reduced diurnal tidal signal can be observed with a underlying pattern of spring tidal pumping. Pattimore's Lagoon can be observed to experience almost no diurnal tides but can be seen to vary slightly with rainfall events and average water level variations in Lake Conjola.

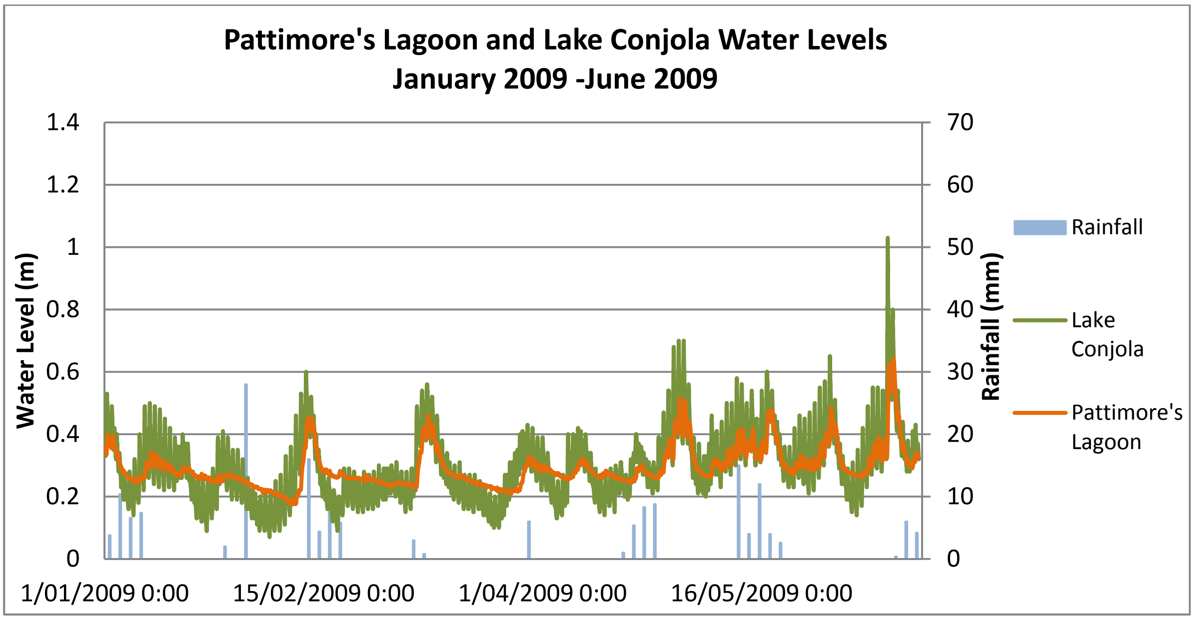


Figure 6.8: Water level variation from January to June 2009. This graph shows the tidal pattern recorded at Lake Conjola entrance and Pattimore's Lagoon during increasingly shoaled entrance conditions. A further reduced diurnal tidal signal can be observed with a larger underlying pattern of spring tidal pumping. Pattimore's Lagoon can be seen to experience greater water level variations though rainfall appears to decrease. This could imply the spring tidal pumping is becoming and important factor controlling water level variations in Pattimore's Lagoon.

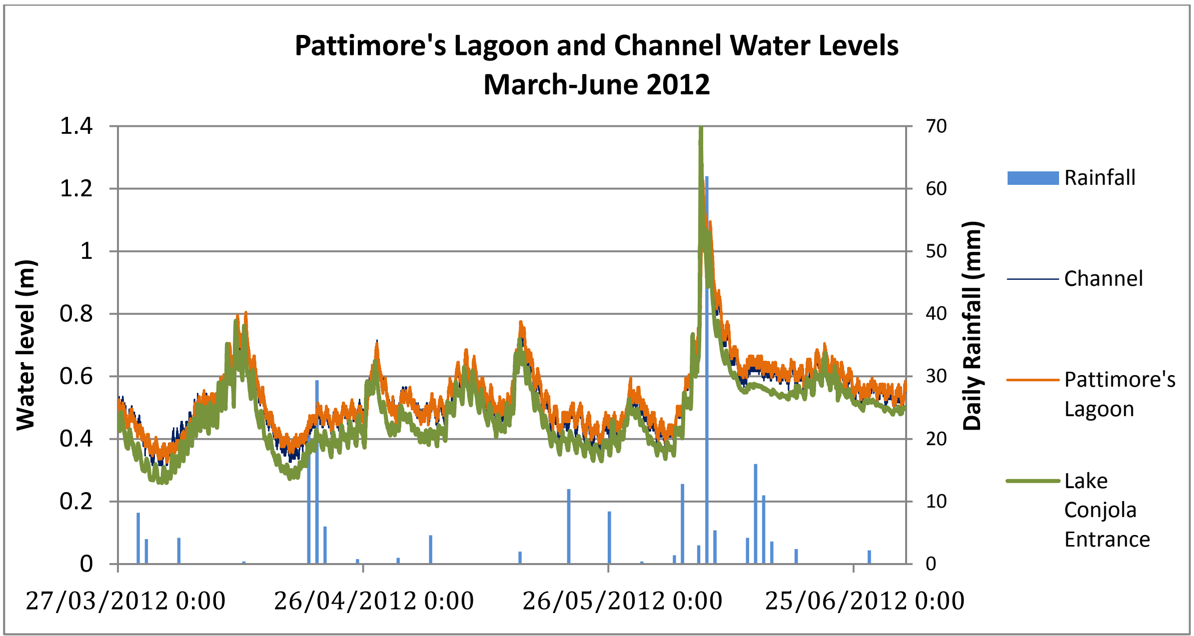


Figure 6.9: Water level variation from March to June 2012. This graph shows the tidal pattern recorded at Lake Conjola entrance, Pattimore's Lagoon and the channel during nearly closed entrance conditions. A spring tidal pumping cycle can be observed with a much reduced diurnal tidal signal over the top. Pattimore's Lagoon can be seen to experience greater a similar diurnal tidal signal to Lake Conjola and much more tidal variation then seen in any other study period.

6.2.2 Tidal Attenuation

This section examines the tidal planes i.e. the degree of tidal attenuation, within Lake Conjola. To investigate the tidal attenuation experienced in Pattimore's Lagoon, the Mean High Water Spring, Mean Low Water Spring, Mean High Water Neap, and Mean Low Water Neap were calculated for the open ocean, Lake Conjola's entrance (site 2, Figure 6.11), the channel, and Pattimore's Lagoon (gauges in Figure 6.2) for April, 2012. The tidal planes for this period can be seen in Figure 6.10. These tidal planes showed very little tidal attenuation between Lake Conjola's entrance and Pattimore's Lagoon. It also showed Mean Low Water Neap tides lower than the Mean Low Water Spring. This is different to what is commonly expected, that the neap tides would fall within the spring tides, this difference was assumed to result from spring tidal pumping within the Lagoon at this periods. It was also seen that water levels increase with distance from the ocean due to geomorphic constriction and neap tides actually increase in the channel and Pattimore's Lagoon.

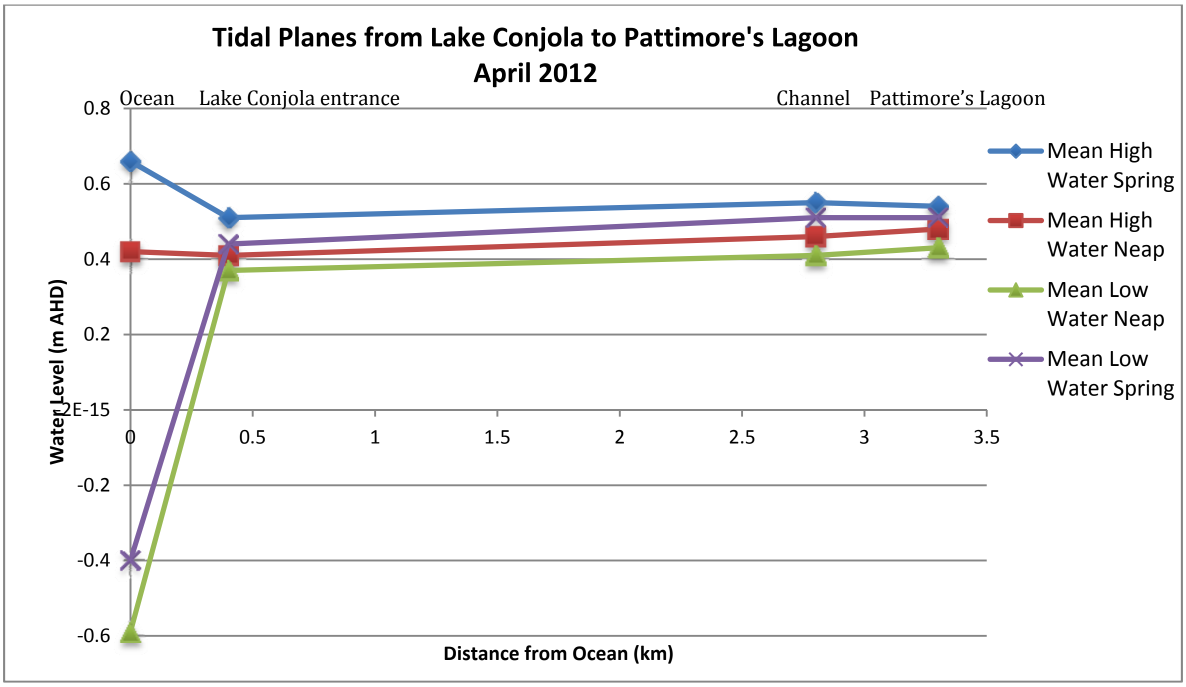


Figure 6.10: Tidal Planes from Lake Conjola-Pattimore's Lagoon, April 2012. Ocean tides recorded at Jervis Bay. Locations of the Lake Conjola's entrance, channel and Pattimore's Lagoon recorders can be seen in Figure 6.2.

As the tidal attenuation was drastically smaller than expected, the results were compared to the tidal plane model for Berringer Lake from a data collection report on Lake Conjola (Manly Hydraulics Laboratory, 2009). Berringer Lake is a similar distance from the ocean as Pattimore's Lagoon, however, it was expected that Pattimore's Lagoon would experience greater tidal attenuation due to a much narrower and longer connection to Lake Conjola, as well the presence of the collapsed weir. However, it was seen that Pattimore's Lagoon experienced much less tidal attenuation then seen in Berringer Lake (Figure 6.12, site locations Figure 6.11). These findings indicate that the tidal attenuation model created for Pattimore's Lagoon shows less tidal attenuation than would be seen during open, or partially shoaled entrance conditions. The very reduced diurnal tidal signal and prevalence of spring tidal pumping are most likely the cause of this reduced tidal attenuation. This study will assume that this model is unrepresentative of all tidal conditions within the system. Further study would need to be undertaken before any conclusions could be drawn.

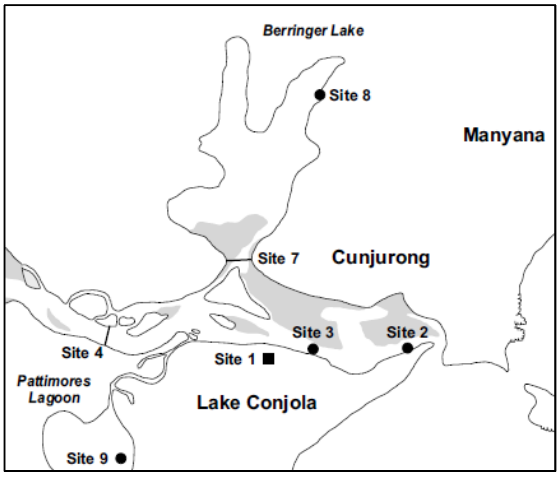


Figure 6.11: Tidal gauge locations used by Manly Hydraulics to create the tidal plane models for Berringer Lake. Site 0, ocean tide recorder, a t Jervis bay not pictured (Manly Hydraulics Laboratory, 2009).

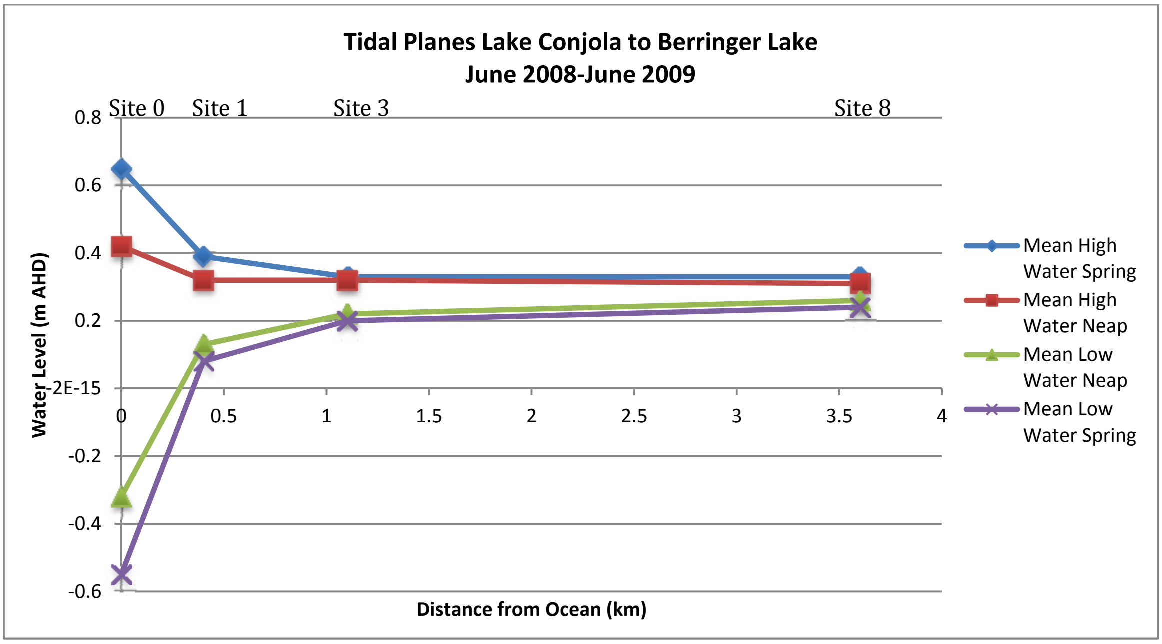


Figure 6.12: Tidal planes of Lake Conjola to Berringer Lake from 2008-2009, adapted from DECCW Lake Conjola Data Collection September 2008-June 2009, Manly Hydraulics Laboratory (2009). Site locations located in Figure 6.11

6.2.3 Effectiveness of the Weir

In the early 1980 a weir was built at the entrance of Pattimore's Lagoon in an attempt to return the lagoon to its pre-canal estate development condition by reducing the amount of tides reaching the lagoon. Subsequently, the weir collapsed a few years later rendering it less effective than intended. This section examines the current effectiveness of the collapsed weir in reducing tides within Pattimore's Lagoon. This was assessed by installing two tidal recorders, one below the weir in the channel and above the weir in the center of Pattimore's Lagoon from March to July 2012

Observations from the 1st-3th of April showed no noticeable tides occurred within Pattimore's Lagoon, while tidal fluctuation of 5-6cm were seen in the channel and 6-7cm at Lake Conjola Entrance. During this period water levels in Pattimore's Lagoon and the channel were below 0.45 m AHD, (Figure 6.13).

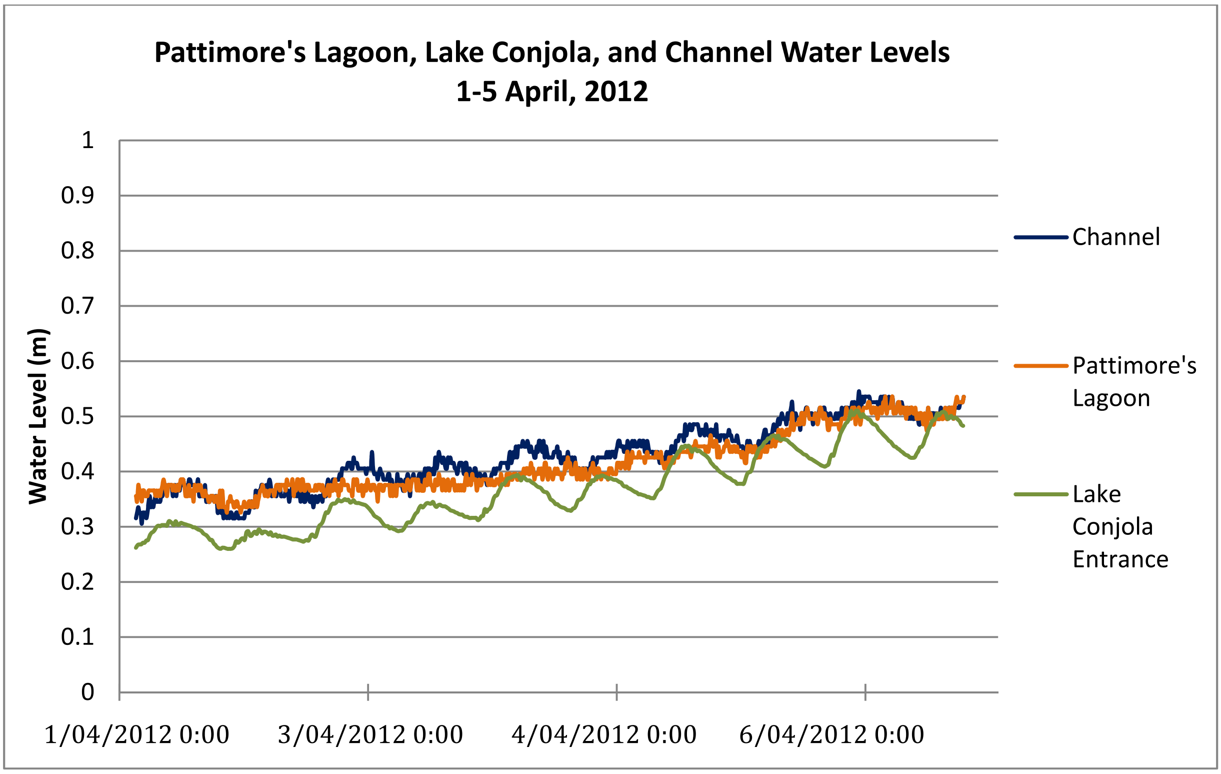


Figure 6.13: The water levels of Pattimore's Lagoon, the Channel, and Lake Conjola from 1-5 April 2012.

When water levels in the channel are above 0.45m AHD, tidal signal in Pattimore's Lagoon were seen to be very similar to that of the channel, suggesting a less effective weir. From 6th-10th April 2012 water levels in Pattimore's Lagoon were over 0.45m datum, tidal fluctuations of 6-8cm where seen in both Pattimore's Lagoon and the channel, while at Lake Conjola's entrance there was a tidal signal was 6-12 cm, (Figure 6.14). The weir height was not able to be measured in AHD, due to tree cover blocking satellite connection, but from these findings it can be assumed that the weir is roughly 0.45 m AHD, or becomes ineffective at this level.

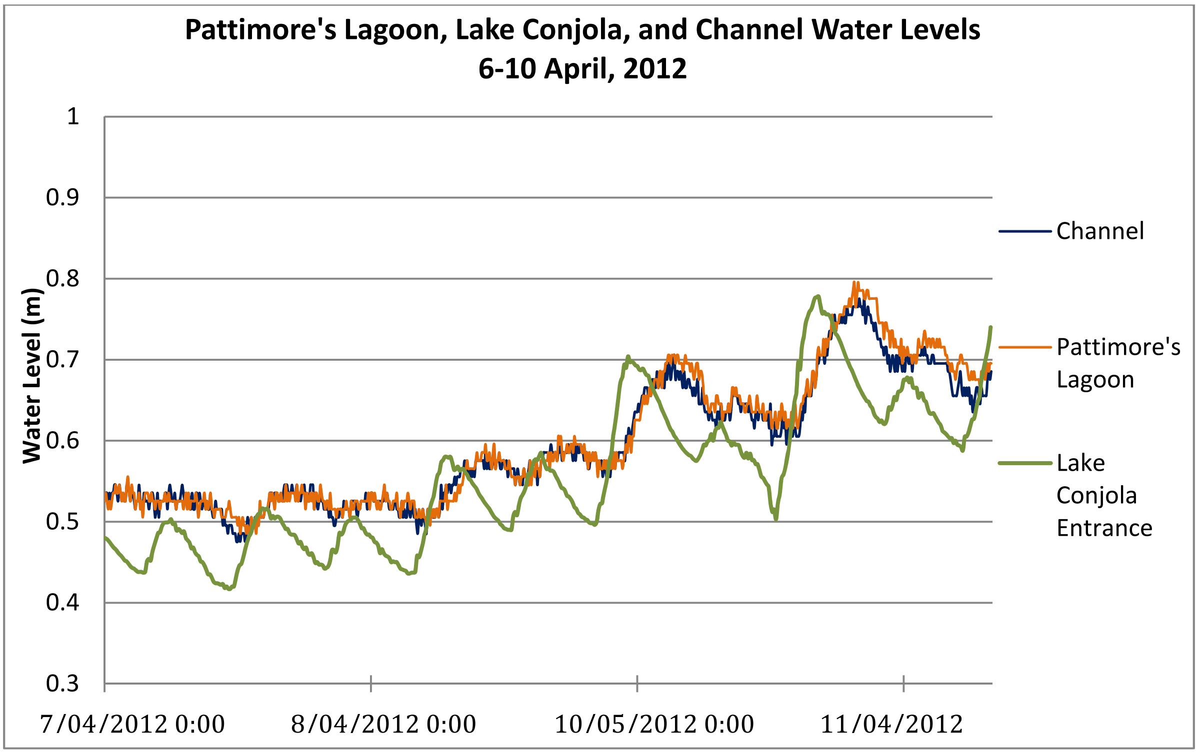


Figure 6.14: The water levels of Pattimore's Lagoon, the Channel, and Lake Conjola from 1-5 April 2012.

Though the data from 2008-2009 does not have water levels from the channel, however, tidal attenuation modeling shows that when water levels in the channel are 0.45 m Lake Conjola entrance would be around 0.40 m, allowing water levels in Lake Conjola to be used to assess connectivity in Pattimore's Lagoon.

From 10-16 of October 2008, water levels in Lake Conjola were under 0.3 m AHD, and there is no tidal signal in Pattimore's Lagoon (Figure 6.15). One month from 15-19 of November 2008, Lake Conjola water levels was under 0.40 m, but the high tides level was over 0.4. It was seen that during this period that during high tide flowed over the weir into Pattimore's Lagoon filling the lagoon. Water levels were, however, too low to drain back out during low tides, so that the lagoon progressively filled. During this time water level in Lake Conjola steadily decreased while water levels in Pattimore's Lagoon gradually increased.

Just days later, 20-27 of November 2008, water levels exceed 0.4 m AHD, and a tidal signal appears in Pattimore's Lagoon and can be observed to increase with rising water levels (Figures 6.16).

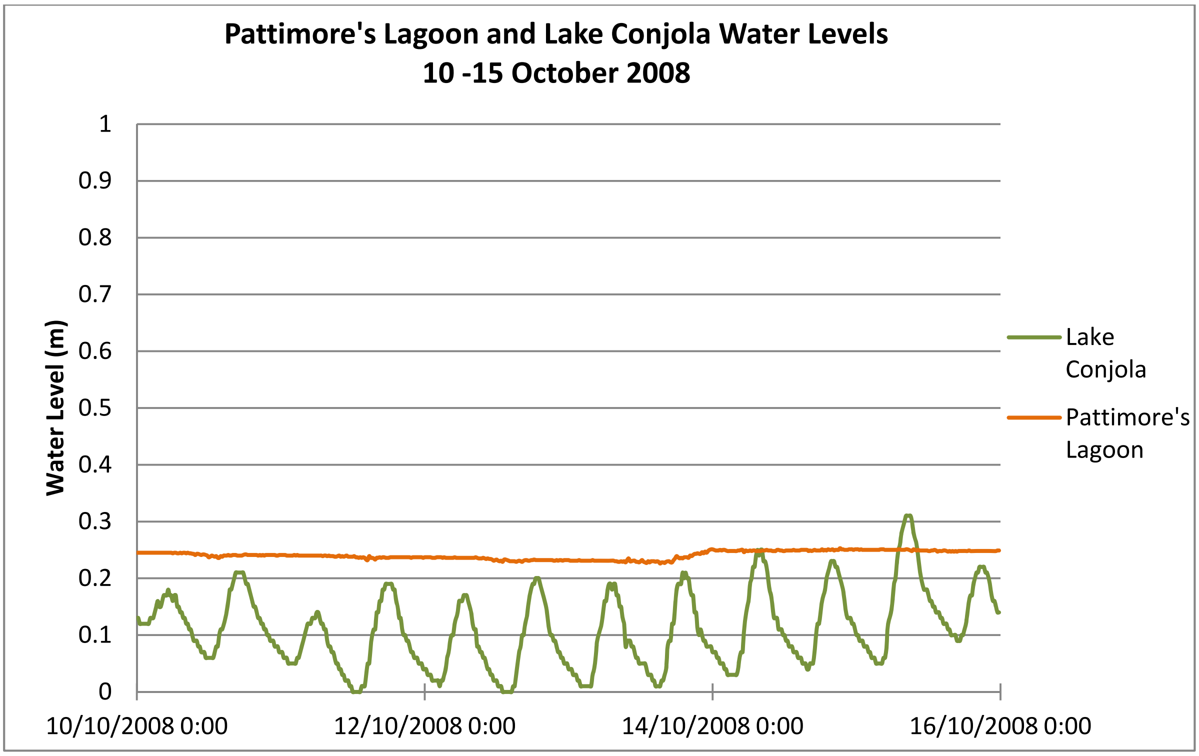


Figure 6.15: Water levels in Pattimore's Lagoon and Lake Conjola from 10-15 October 2008.

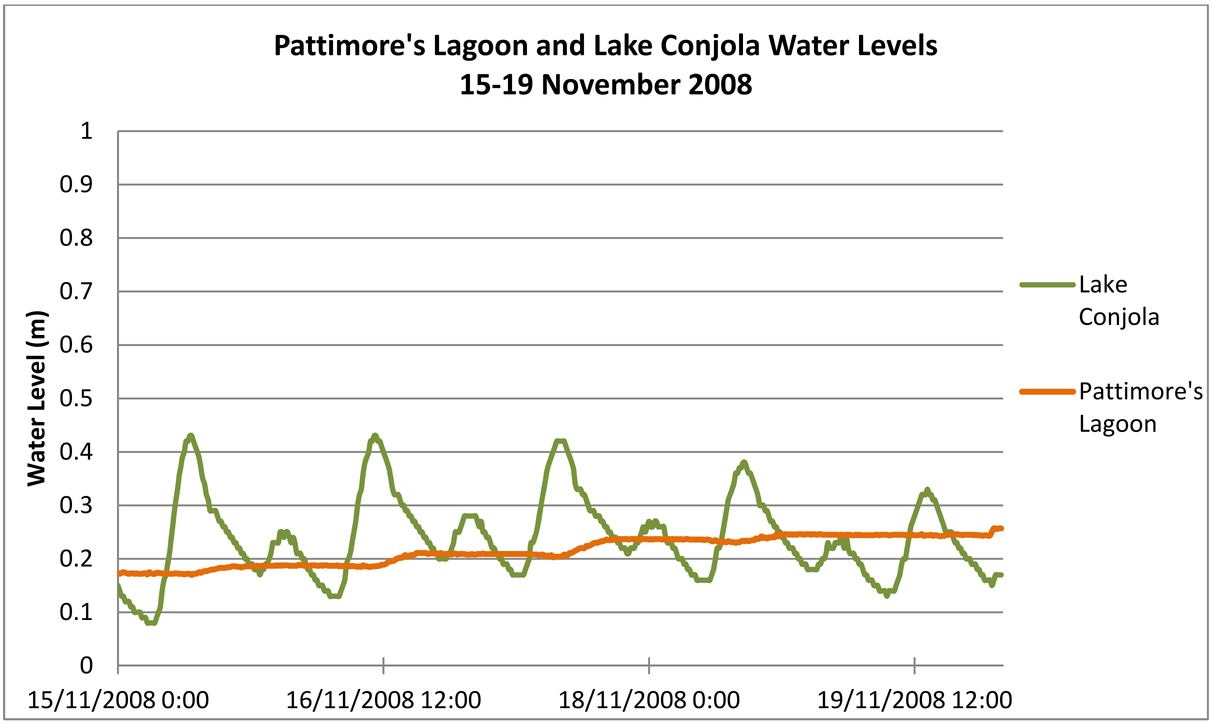


Figure 6.16: Water levels and rainfall data from Pattimore's Lagoon and Lake Conjola from 20-25 November 2009.

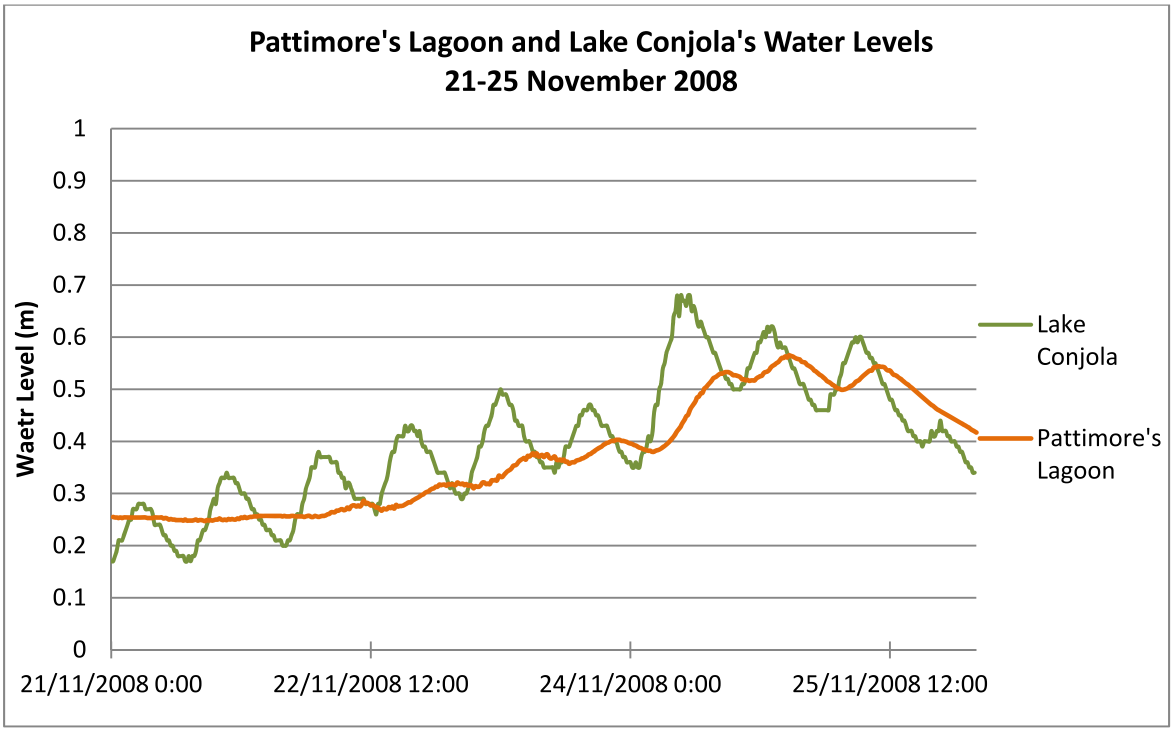


Figure 6.17: Water levels in Pattimore's Lagoon and Lake Conjola from 20-25 November 2009.

The tidal data for Lake Conjola from 2005 (Figure 6.4) shows the diurnal high tide is typically above 0.4 m AHD. This would suggest that during open entrance conditions Pattimore's Lagoon would have tide washing over on a nearly daily basis. This could suggest that during the open entrance conditions, Pattimore's Lagoon is experiencing the third category of connectedness, one which allows high tide spill over rather than being connected during a full tide cycle.

During this investigation it was seen that the tidal connection between Pattimore's Lagoon and Lake Conjola was mainly controlled by two factors, the water level height in Lake Conjola and the size of the tides. It was found that multiple states of the degree of connectedness occur;

1. No connection occurs, Pattimore's Lagoon and channel have water levels lower than the weir and tides are to small to flow over the weir.
2. Complete connection occurs, Pattimore's Lagoon and Lake Conjola water levels are above the height of the weir. During such conditions Pattimore's Lagoon experiences the similar tidal regime as Lake Conjola, with some level of tidal attenuation due to distance from entrance and narrowness of channel.
3. Partial connection occurs when Pattimore's Lagoon and channel have mean water levels lower than the weir, but high tides flow over the weir, in this case water spills into Pattimore's Lagoon at high tide levels, but is unable to drain out at low tide. This results in a gradual filling of Pattimore's Lagoon.

6.2.4 Effect of tides on salinity in Pattimore's Lagoon

This section examines the influence water level and entrance conditions on salinity in Pattimore's lagoon. Water quality data for Pattimore's Lagoon from 2007-2011 was supplied by Shoalhaven City Council. This data was sampled 4 times a year starting in July 2007. Salinity was plotted against the M2 tidal constituent to assess if there is a direct relationship between the size of the tides, and thus entrance conditions, and salinity in Pattimore's Lagoon. As is shown in Figure 6.18, there is a very slight polynomial relationship, this would imply that salinity is highest when tides are moderately small and the entrance is partially shoaled. However, more data would be required before any conclusions could be drawn.

A second graph compares to water level to salinity in Pattimore's Lagoon shows a slight trend suggesting that as water levels increase, salinity decreases (Figure 6.19). This could result from periods of high water levels occurring when entrance was closed and the lagoon was receiving significant freshwater inflow, while in open entrance conditions, the water level would be lower and the salinity similar to marine values (i.e. 35 PPT). Similarly, in instances when the entrance is closed and there is very little freshwater input, water levels would be very low and salinity higher than marine due evaporation in Pattimore's Lagoon exceeding freshwater flow and increasing salinity. However more data is necessary before any substantive conclusions can be made.

The salinity trace in Pattimore's Lagoon over the last five years shows a gradual increase until February of 2009, followed by a decrease, some fluctuations, until the present time (Figure 6.20).

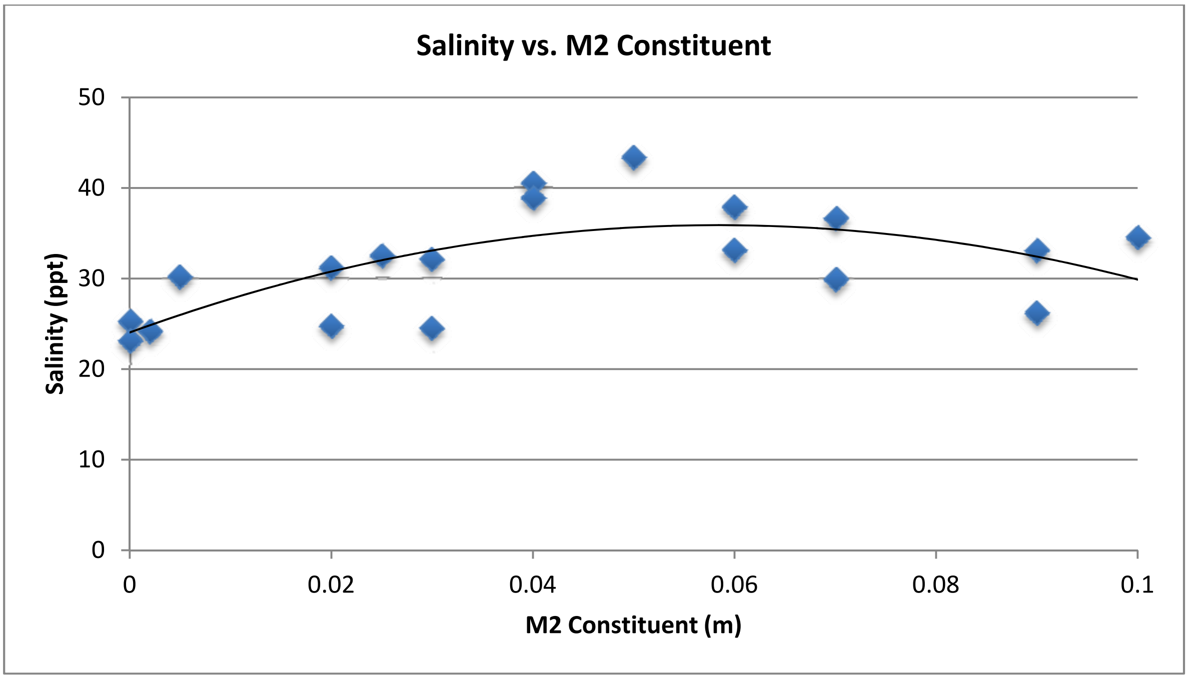


Figure 6.18: Graph correlation salinity in Pattimore's Lagoon to the M2 tidal Constituent at Lake Conjola's entrance, and thus the correlation of Salinity in Pattimore's Lagoon to the level of Lake Conjola Entrance shoaling.

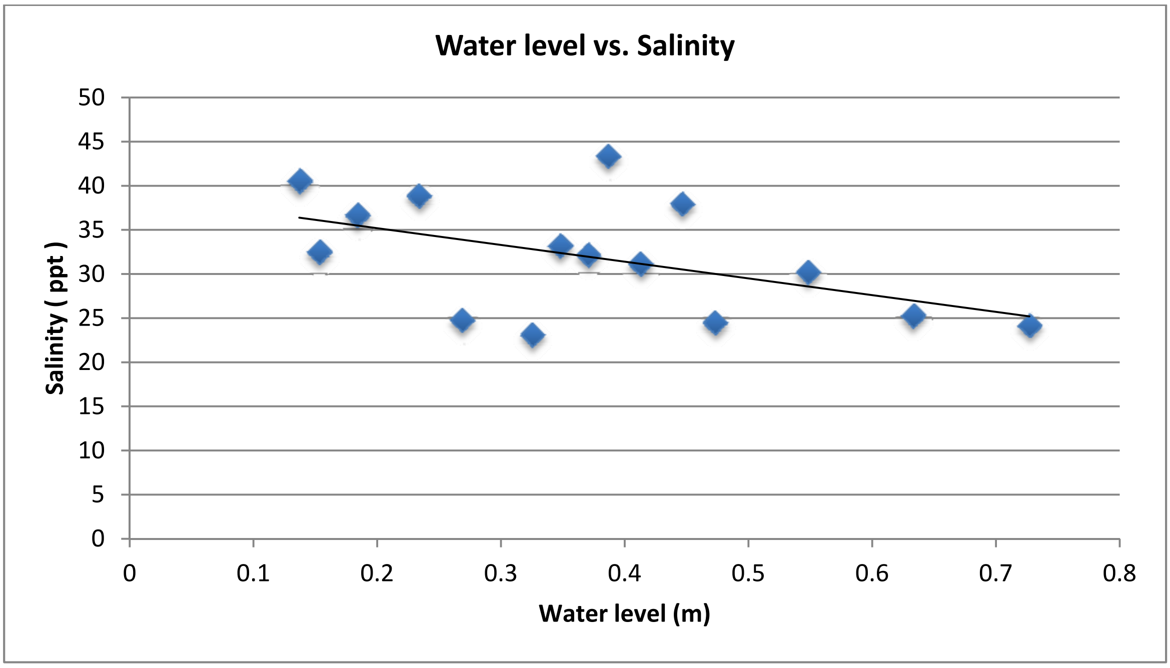


Figure 6.19: Graph showing the Correlation of Salinity in Pattimore's Lagoon to the Water Level in Lake Conjola's entrance.

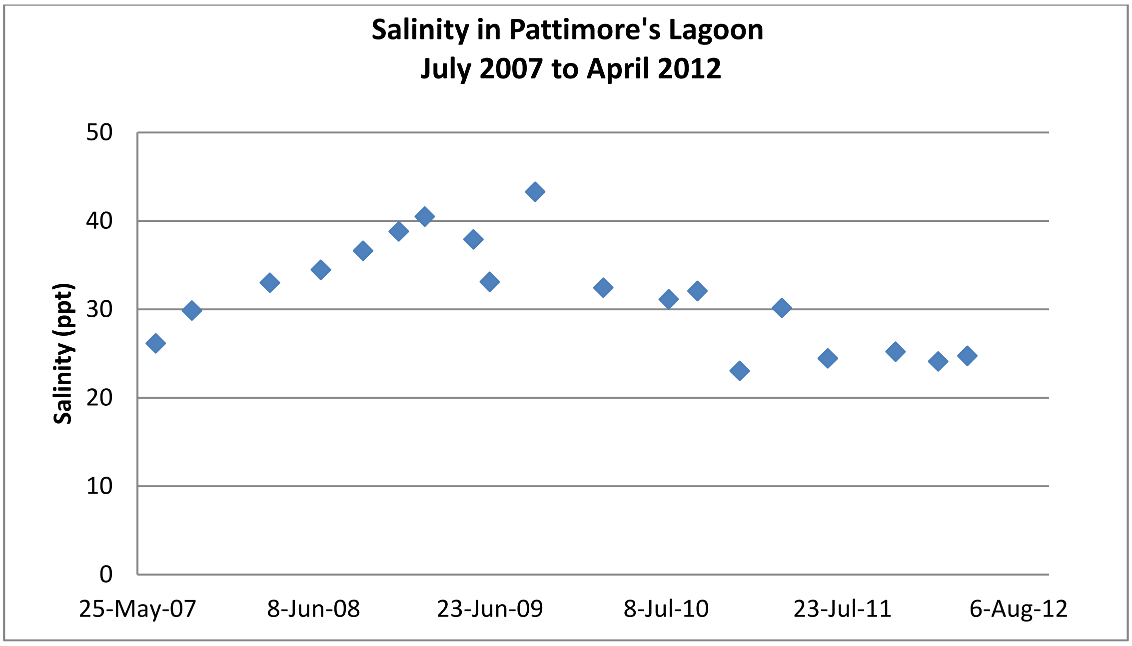


Figure 6.20: Graph showing the Salinity in Pattimore's Lagoon from July 2007 to April 2012.

Summary

Lake Conjola tidal signal is heavily influenced by the estuary's entrance conditions. It has been noted that as the entrance progressively shoals, the diurnal tidal signal decreases while the prevalence of spring tidal pumping increases. This influences water levels and tidal inundation throughout the estuary. The collapsed weir is effective at stopping tidal penetration into Pattimore's Lagoon when water levels in the channel are under 0.45 m, (0.4 m at Lake Conjola's entrance). Over this water level, high tides begin to spill over the weir into Pattimore's Lagoon and gradually fill the system. When the average daily water level is over the weir height, such as seen during nearly closed entrance conditions, Pattimore's Lagoon experiences similar tidal pattern as Lake Conjola and can be assumed to be connected to the estuary system. Salinity within Pattimore's Lagoon is influenced by both entrance conditions and water levels in Lake Conjola. All results show that Pattimore's Lagoon is not completely isolated for Lake Conjola, and still heavily influenced conditions within the estuary.

Chapter 7. Vegetation Zones

This chapter discusses the various vegetation zones around Pattimore's Lagoon and models the frequency and duration of inundation of each vegetation zone under various entrance conditions. It discusses the various inundation patterns the vegetation has experienced over 3 periods tide recording.

7.1 Methods

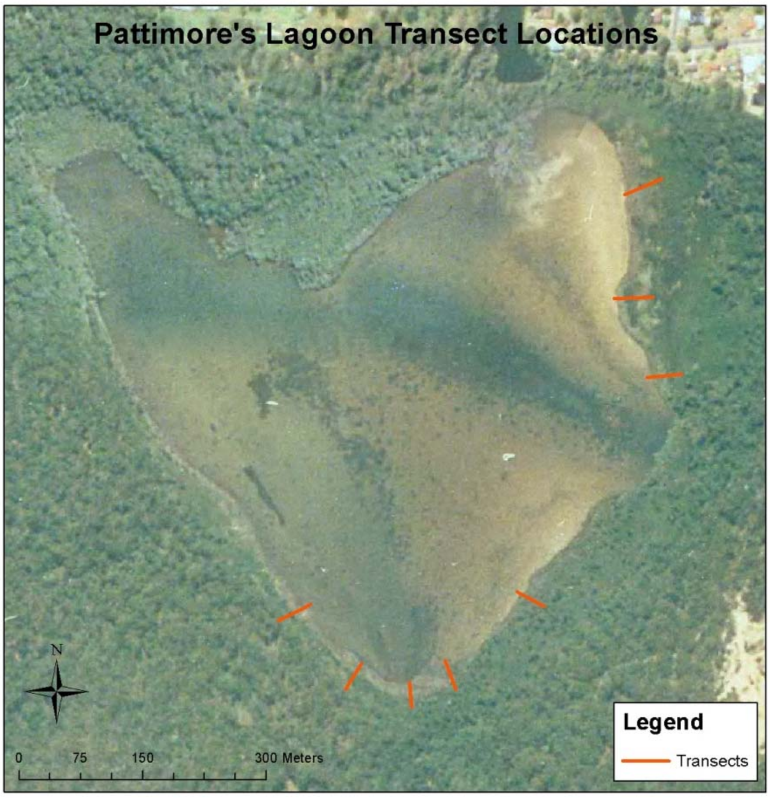


Figure 7.1: Location of vegetation transects around Pattimore's Lagoon take on 31 July 2012.

Eight vegetation transects radiating out from the water's edge were recorded around Pattimore's Lagoon. The location of each transect can be seen in Figure 7.1. Along each transect vegetation species were identified and major vegetation zones recorded. The elevation of each vegetation zone was measured using a Trimble R7 GNSS receiver as a base station and a Trimble R8 GNSS system as a receiver. This system records positions within an accuracy of centimeters (Trimble Navigation Ltd, 2012). The RTK measures points on the ellipsoid and applies a block shift equation convert these measurements to the Geoid/AHD. Currently the AusGeoid09, Australia's newest Geoid model for converting ellipsoidal heights to AHD heights is accurate to 0.03 m across most of Australia, but can vary more than that in some areas (Brown, 2010).

The average, upper and lower positional heights of each vegetation zone was found and correlated with the tidal record to model the tidal inundation frequency and duration of each vegetation zone under the different tidal condition.

7.2 Results

The main vegetation species recorded included *Juncus, Baumea articula, Phragmites australis* (always mixed amongst either the *Juncus* or *Baumea articula*), *Melelueca, Casuarinas*, and *Eucalyptus*. There were recorded as zones with various elevations and distances from the water's edge. Tree cover in the *Eucalyptus*, and *Casuarinas* zones made the GPS readings of elevation fairly inaccurate. Examples of some of the transects seen can be seen in Figure's 7.2-7.4

Table 7.1: Average, lowest, and level of variation of vegetation zones elevations recorded in Pattimore's Lagoon.

Species	Average positional height (m)	Lowest positional height (m)	Highest positional height (m)	Variance from lowest to highest positional height (m)
Avicennia pneumatophores	0.20	0.183	0.225	0.042
Avicennia Mangrove	0.41	0.323	0.499	0.176
Juncus	0.44	0.347	0.590	0.243
Baumea articula	0.31	0.284	0.337	0.053
Phragmites australis	0.50	0.284	0.522	0.238
Meleleuca	0.61	0.469	0.662	0.193
Casuarinas	0.56	0.379	0.750	0.371
Eucalyptus	3.43	1.794	5.100	3.306

Average vegetation zones positional heights were plotted to model tidal inundation frequencies, (Figure 7.5). Although it could be argued that the lowest found elevation of the vegetation zone are more representative, it was found that the average heights of vegetation zones across all transects were representative, as often the lowest vegetation zones were found to be outliers. Thus the average height of each vegetation zone was used to model inundation, as such, local variation throughout the lagoon should be taken into account when viewing results.

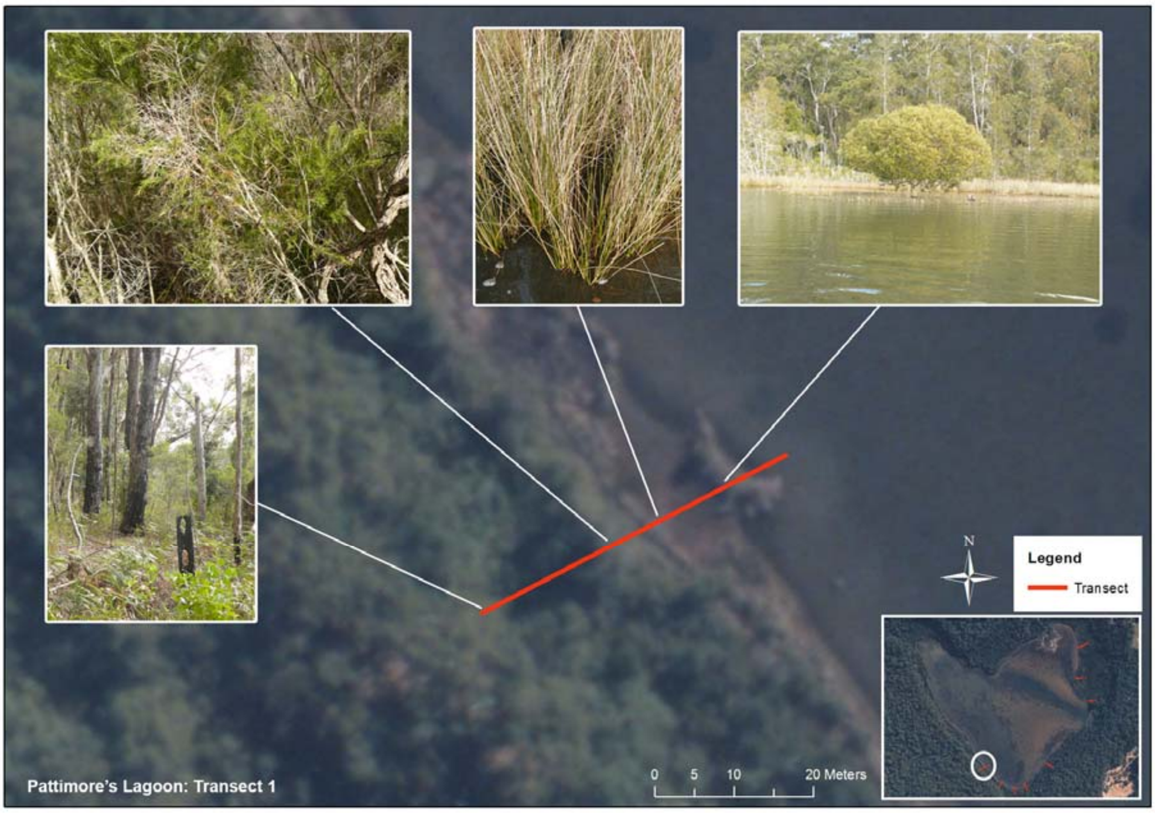


Figure 7.2: Vegetation Transect 1 with photos of some of the distinct zones seen.

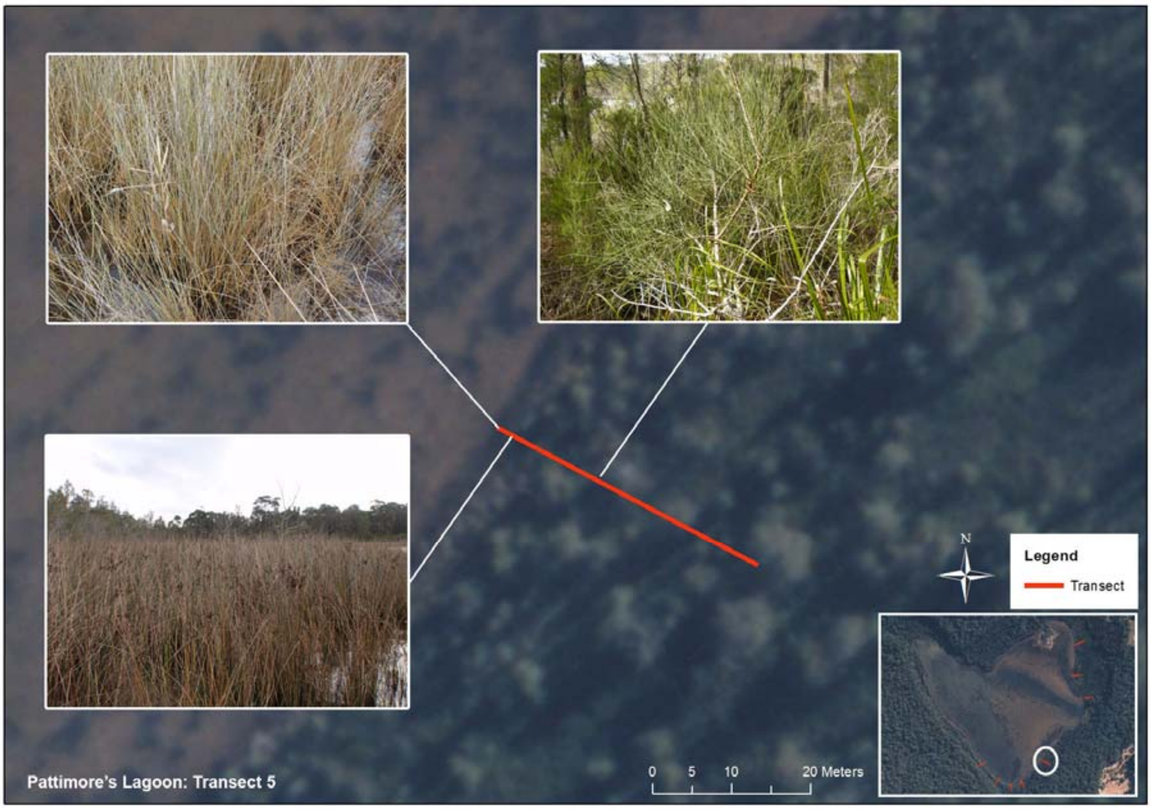


Figure 7.3: Vegetation Transect 5 with photos of some of the distinct zones seen.

Figure 7.4: Vegetation Transect 7 with photos of some of the distinct zones seen.

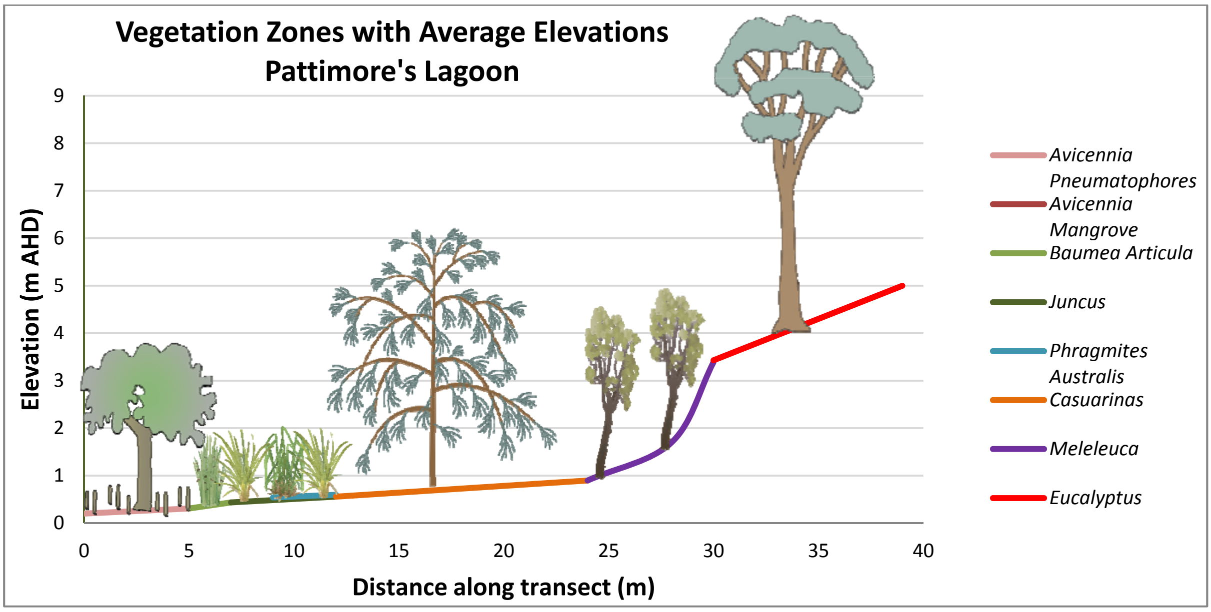


Figure 7.5: Graph of average vegetation zones with average heights and spatial distributions seen.

If the tidal pattern in Pattimore's Lagoon was similar to that seen in open estuaries, the vegetation zones could be divided into standard inundation categories, such as 'inundated by spring high tides', as used by Watson (1928). However, this system is highly variable, and does not follow ocean tidal cycles. For the purpose of this thesis, the categories of inundation will be simplified as follows;

Never 0%
Rarely 10%-20%
Sometimes 20%-50%
Often 50% -80%
Constantly 80%-100%

Examining Figures 7.6-7.8, it can be observed different tidal regimes occurred in Pattimore's Lagoon leading to different inundation patterns throughout each period.

In partially shoaled conditions between September to December 2008, *Casuarinas* were only inundated twice over the four months, both times for less than one day, while grasses would have been inundated for less than 13% of the time (Figure 7.7). Using the average height of 20 cm for the pneumatorphores, (Booker et al., 1998), it was seen that these would have been completely covered and unable to breathe twice for up to 3 days, which equates to 4% of the 4 month period (Figure 7.6).

As shoaling increased vegetation became inundated more frequently, between January to June 2009, grasses became inundated 28 % of the time, for durations of up to a week (Figure 7.8). The average 20 cm long pneumatorphores would have experienced complete inundation for up to 8 % of the time, but never more than a few days (Figure7.7).

From March- July 2012, when the entrance was near closure, *Meleleuca* became inundated for the first time. The *Casuarinas* were inundated 7 times over the 5 months, and for up to 20 days at a time. The lower lying grasses were inundated 100% of the time, and the higher grass species over 60% of the time. The average 20 cm long pneumatophores would have been completely covered 94% of the time (Figure 7.8).

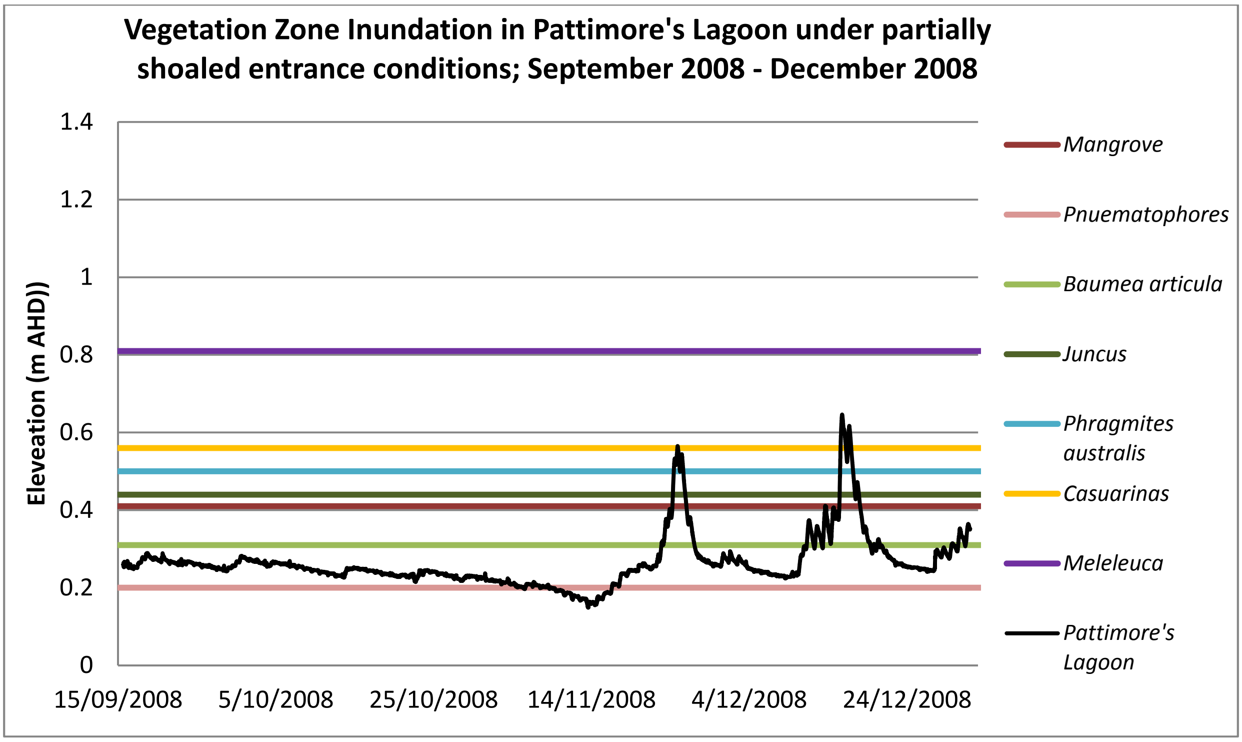


Figure 7.6: Vegetation frequency and duration of inundation in Pattimore's Lagoon from September-December 2008, under partially shoaled entrance conditions, plotted with the average positional height vegetation zones, excluding eucalyptus.

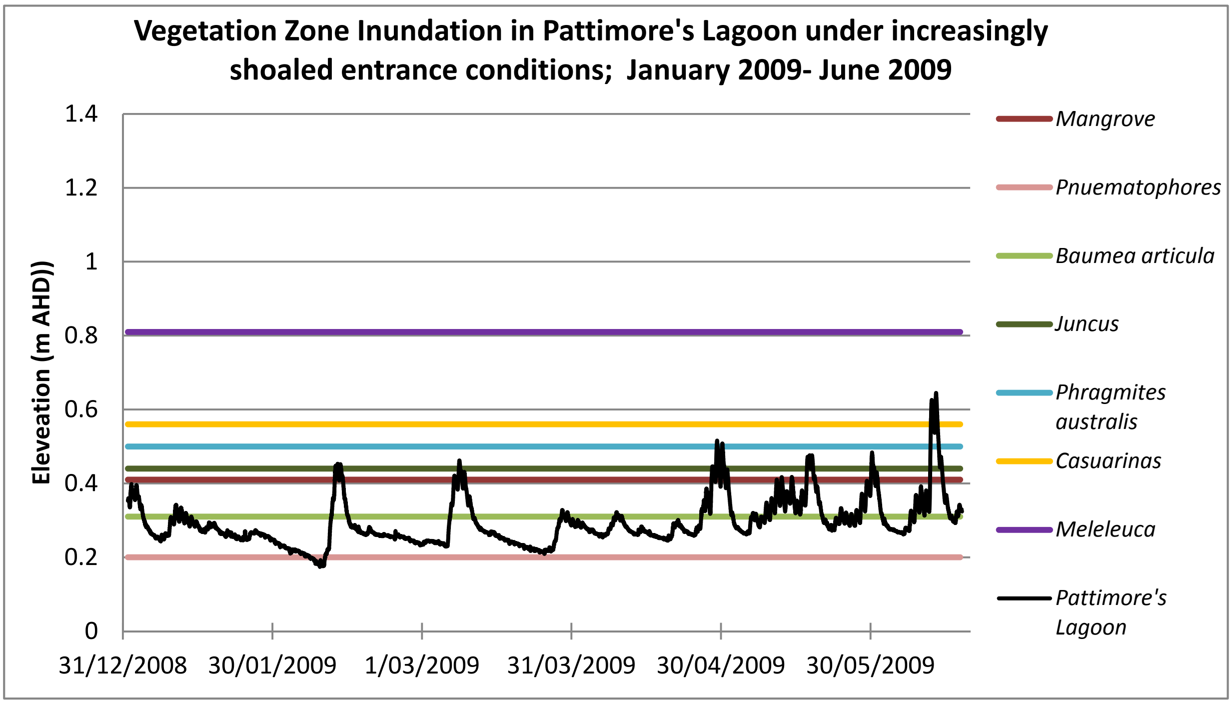


Figure 7.7: Vegetation frequency/duration of inundation in Pattimore's Lagoon from January-July 2009, under increasingly shoaled entrance conditions, plotted with the average positional heights of vegetation zones, excluding eucalyptus.

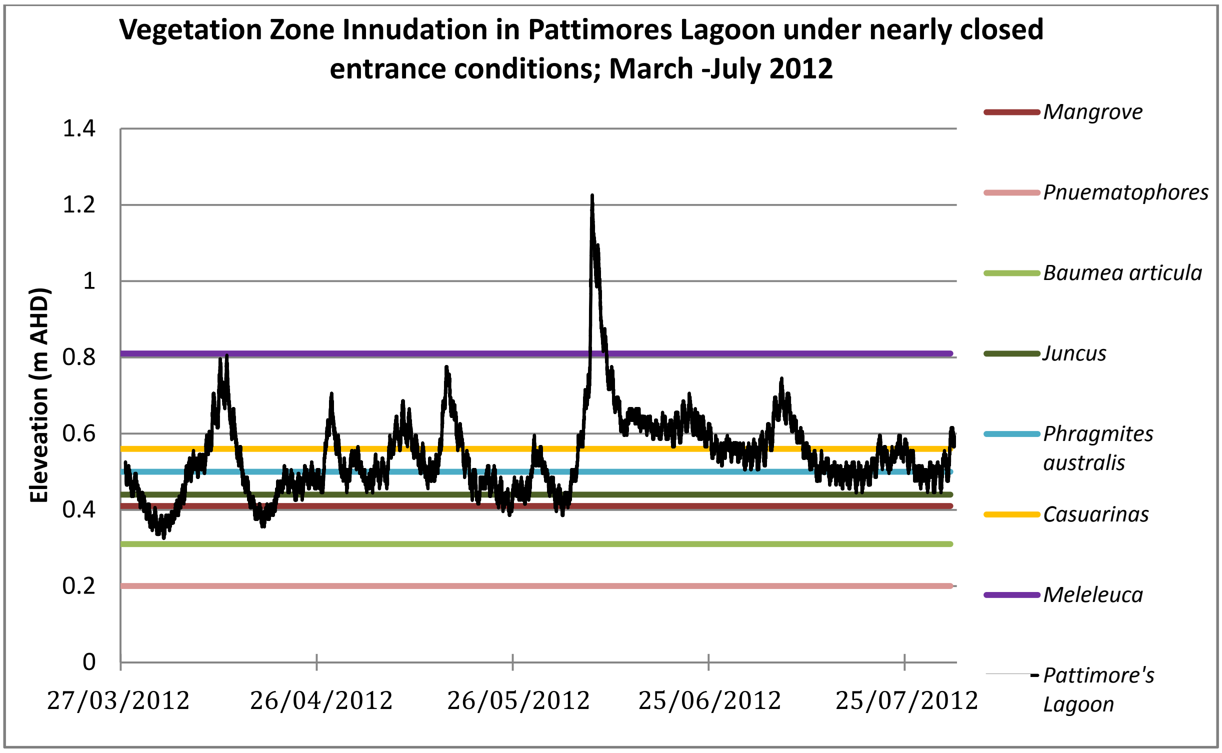


Figure 7.8: Vegetation frequency and duration of inundation in Pattimore's Lagoon from March-July 2012, under nearly closed entrance conditions, plotted with the average positional height of each vegetation zone, excluding eucalyptus.

All study periods presented here occurred during partially shoaled to nearly closed entrance conditions. In the case of open entrance conditions, it is assumed that the vegetation would experienced different tidal inundation frequencies and durations than any depicted above. The variety of factors which influence water level and inundation frequency make it difficult to predict what those environments would be.

7.2.1 Mangroves

During the vegetation surveys it was noted that Pattimore's Lagoon was populated by a very large number of *Avicenna* Mangrove. Historically it has been documented that Pattimore's Lagoon had very few mangroves. For example, the Findlay (1988), it was noted that only two mangroves were present.

In 2012, many mangroves were seen around the Lagoon. One survey along the north-east section f the Lagoon recorded 26 juvenile and mature mangroves, (Figure 30). The finding of greatly increased number of mangroves species could be a result of two things;

1. Pattimore's Lagoon's past environment could not support mangroves, and recently there has been a change in environment which now allows mangroves to colonize the area.

2. Pattimore's Lagoon's past environment could support mangroves, but the propogules were unable to reach the lagoon until recently, implying flow through the original creek was not sufficient to transport mangrove propogules. However, a small delta at the entrance of the original lagoon, as seen in the historic aerial photographs (Figure 5.3), implies there was sufficient flow to transport mangrove propogules.
3. Due to wide scale change, mangroves have increased throughout Lake Conjola and as a result have colonized Pattimore's Lagoon. Such changes could have resulted from alterations in entrance conditions.

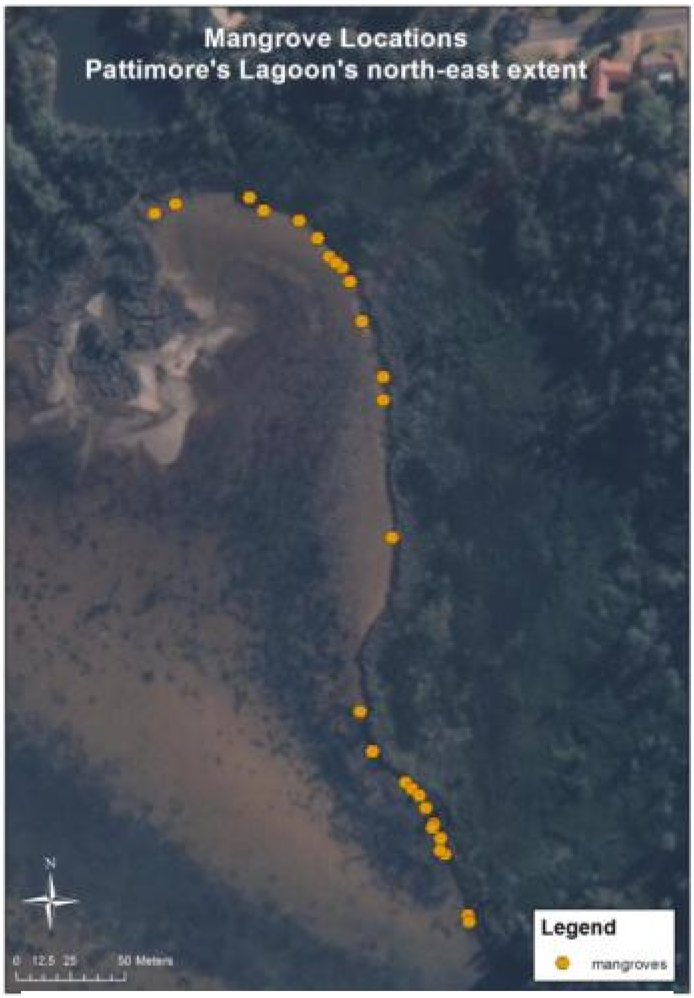


Figure 7.9: Recorded mangrove locations along a short stretch of Pattimore's Lagoon's north east bank.

Summary

The vegetation species surrounding Pattimore's Lagoon experience different tidal inundation frequencies and durations under different entrance conditions and water levels in Lake Conjola. The variation between partially shoaled to nearly closed entrance conditions showed a up to 90% increase in inundation. This demonstrated that the vegetation in this system would have to have adapted to a highly variable inundation regime. The observation of a large increase in mangroves around Pattimore's Lagoon suggests a change within the system has occurred over the last 50 years, either to the ability of pneumatophores to enter Pattimore's Lagoon, tidal regime within Pattimore's Lagoon, or estuary wide change throughout Lake Conjola.

Chapter 8. Discussion

The major focus of this thesis was to increase the understanding of Pattimore's Lagoon's past and present environment in order to assist management decisions and improve environmental outcomes. There has been suggestions, by the local community and government agencies, that Pattimore's Lagoon should be restored to its pre-European state (Shoalhaven City Council, 1998). However, very little research has been undertaken on the current functioning of Pattimore's Lagoon, and even less on how it operated prior to development of the canal estate and/or European arrival in the region. This thesis investigated past (palaeo) conditions in Pattimore's Lagoon, surveyed evidence for recent change in the lagoon experienced in the last 50 years and examined its current state and behavior. This chapter discusses the results of this investigation from proceeding four chapters to develop a broad model of past and present environmental conditions within Pattimore's Lagoon.

8.1 The Pre-European/Pre-Canal Estate environment in Pattimore's Lagoon

"*Managing ecosystems without any knowledge of their history may well invite disaster, simple description is inadequate for understanding rates, directions and magnitudes of change in complex systems"* (Clark and Wasson, 1988)

The Estuary Management Plan for Lake Conjola (1998) and the more recent Estuary Management Plan Review (GHD, 2012) outlined water quality objectives for the estuary. One of the objectives of the plans , objective WQ 7, is to "Restore Pattimore's Lagoon Salinity to the appropriate regime" (p 3.1.13 Shoalhaven City Council, 1998). However, there is no definition, or mention of what the "appropriate" salinity regime is, or even what is meant by 'appropriate'. 'Appropriate' could mean most manageable or sustainable regime for the current lagoon system, or the natural pre-European salinity regime? For the purpose of this thesis, the appropriate salinity regime is understood to be the historic, pre-canal estate salinity regime, on the basis that there have been calls to return the lagoon to its pre-European state (GHD, 2012, Shoalhaven City Council, 1998).

Current understanding of the evolution of Pattimore's Lagoon is heavily shaped by an honours thesis from the University of New South Wales (Findlay, 1988). This thesis assessed the environmental history and trophic status of Pattimore's Lagoon via shell fauna and diatoms within cores extracted from the lagoon which were used to interpret palaeo-conditions in Pattimore's Lagoon (Findlay 1998).

Two distinct periods were identified within Pattimore's Lagoon, an estuarine period and a lagoonal period (Findlay, 1988). The estuarine period was defined as the time period when Pattimore's Lagoon was directly part of Lake Conjola estuary, i.e., not separated with a connecting channel as it now is. During this period it would have experienced the same conditions as the rest of the estuary. This period was believed to have occurred from ~5000 years BP to ~4100 years BP. The lagoonal period, in which Pattimore's Lagoon was significantly isolated from Lake Conjola, was believed to have begun around 3900 years BP. During this period, Pattimore's Lagoon was believed to be isolated from the Lake Conjola, but in a similar fashion as seen today with periodic connection via a long narrow channel and inundated during spring tides and unusually high water levels (Findlay, 1988).

Analyzing diatoms, Findlay determined that during the lagoonal period, conditions ranged from hypersaline through to saline, and brackish, and possibly even fresh. Findlay outlined the evolution of the salinity of Pattimore's Lagoon's during its isolated lagoon period, in which, firstly the lagoon experienced hypersaline conditions, then progressively freshened, before again becoming hypersaline then returning to freshwater. This stage was believed to be followed by brackish water conditions until a peak in apparent freshness occurred approximately 15 cm from the surface of the core. After 15 cm there was increasing salinity and increased sand deposition until the surface.

Based on these findings this thesis, and Lake Conjola Estuary Management Plan (Shoalhaven City Council, 1998), have defined Pattimore's Lagoon as a "brackish water body undergoing a normal transition to an increasingly freshwater swamp and being progressively invaded by more complex vegetation" (Findlay, 1988). This interpretation has implications for the management of Pattimore's Lagoon and its possible 'restoration'. The robustness of Findlay's (1988) conclusions can be questioned, however. For example, 24 of the 31 diatoms samples examined by Findlay contained 10 or less diatoms, and only 4 samples contained over 100 diatoms, while to be statistically significant over 400 diatoms are necessary. The interpretation of diatoms can also be questioned as Findlay described part of his analysis as "crude…. [with] pennale diatoms [used as] indicators of freshwater [conditions] while centrales diatoms [were used as] indicators of saltwater" (Findlay, 1988). However, species salinity tolerances to not necessary follow these trends. Findlay believed the freshwater environment peaked at 15 cm depth in the cores and interpreted this depth as being representative of the natural (pre-European) salinity. Applying the average sedimentation rate calculated in this study (0.022 cm/

year) implies 15 cm depth equates to ~680 years BP, which is not necessarily representative of the modern environment. In addition, Findlay (1988) extracted cores of only 150 cm depth, therefore the longer term evolution of the estuary was not investigated. This is however important as it puts recent changes within the Lagoon in the context of the lagoon's longer term natural evolution.

8.2 The palaeo-evolution

The cores analyzed in this study generally agree with Findlay's findings, but more closely resemble the evolutionary sequence discussed by Sloss et al. (2010)(Figure 4.3). These cores imply Pattimore's has a complex palaeo-environmental history, where conditions in the lagoon are a function of the geomorphic evolution of the estuary and shorter term palaeo-climate variability.

The deepest part of the cores contained a unit interpreted as marine sand characterized by clean quartz sands. The top of this was dated to 7900± 1200 and is believed to correspond with Post-glacial Marine Transgression sea level rise, during which sea levels rose and flooded the narrow river valley under present day Lake Conjola. During this period present day Lake Conjola and the area of the estuary which is now Pattimore's Lagoon, is likely to have been open to the ocean and would have most like taken the form of an open mouthed bay, a heavily wave dominated environment, allowing the deposition of marine sands. This unit is believed to correlate with the Marine Transgressive Sand layer identified in Lake Conjola by Sloss et al. (2010) (Figure2.4).

After this period, the estuary began to develop into a more isolated system after sea levels stabilised around 6000-6500 years BP, (Sloss et al., 2005, Thom, 1983). This is believed to have resulted from the formation of a barrier system across the bay mouth, formed as sea level rose and stabilized. A muddy sandy unit full of estuarine shell species was dated to begins around 6200 ± 1900, indicating Lake Conjola was protected from the open ocean and that estuarine conditions prevailed. During this period, Lake Conjola would have transitions from a more open wave dominated estuary to a more sheltered barrier estuary, as described in Sloss et al. 2010. This unit is believed to correspond with the Flood Tide Delta facies seen in Lake Conjola cores from Sloss et al (2010) (Figure2.4). During this period Pattimore's Lagoon would have been an openly connected to Lake Conjola estuary.

After about 3500 yrs BP, Pattimore's Lagoon appears to have become separated from the main body of Lake Conjola. The sediments deposited after ~3500 yrs BP consisted of a muddy sandy layer with no shells. This layer is increasingly organic as you move up the profile, implying an increasing terrestrial influenced in the Lagoon. It is thought to be the same unit as the Muddy Sands unit seen in Sloss et al (2010)(Figure 2.4). The unit identified is found in the isolated depositional environments around Lake Conjola, showing that at this point Pattimore's is a highly isolated system by this point (Sloss, 2010). This isolation would have resulted from the deposition of a sediment barrier. The Lagoon may have become permanently isolated following a minor decrease in sea level during the late Holocene as described in Sloss et al., (2007) and Lewis et al., (2008). However, the similarly of this unit with other isolated basins around Lake Conjola implies Pattimore's Lagoon, although isolated, continues to be influenced by processes occurring within Lake Conjola. This results of this core, combined with the model of Sloss et al., (2010) may serve as a model of the development of other similar semi-isolated lagoons along the southeast coast of Australia, such as Berriger Lake in Lake Conjola, the lagoonal arms of Termeil Maroo and Tuross lakes, and Willanga Lake.

This uppermost unit is of most relevance to this the potential restoration of Pattimore's Lagoon as it represents the range of present-day conditions in the lagoon as separated by the longer term history which has been controlled largely by eustatic sea level change during the mid-Holocene. This unit is further investigated in section 8.3.

8.3 Modern evolution

The upper unit of the sediment cores extracted from Lake Conjola best approximates the conditions or range of conditions experienced in the lagoon prior to human modification. Understanding the fine scale salinity regime in recent palaeo (<3500 yrs BP) section of the cores is therefore critical if the Pattimore's Lagoon is to be restored to an "appropriate" salinity regime. This upper most unit consisted of a number of 4 main subunits which show different levels of energy and variability in the system.

Subunit 4, ~3500-1900 yrs BP, was silt dominated sediment with low organic matter and little bioturbation. This suggests it was deposited in low energy conditions without significant biological production. The composition of the subunit 3 (1900-1000 yrs BP) consisted of interbedded sand and muds. Mud layers were found to have moderately high levels of organic matter, while sand layers had very low organic matter. Bioturbation and organic mixing was seen throughout the unit. This period is believed to represent a more variable environment with energy and climatic fluctuations. It can be assumed that the mud layers would have primarily been deposited from fluvial sources and entered from the small creek running into Pattimore's Lagoon. This environment is assumed to have low energy level. The high levels of organic matter would have resulted from high levels of biological activity in the lagoon. This could have been caused by a relatively stable environment with high nutrient levels. The sand would have been deposited from the ocean, and been deposited from either aeolian, tidal, or wave processes. This could imply this period was drier, more storm dominated, or more open to the ocean than the mud depositional layers.

During both periods diatom assemblages were primarily marine, with some euryhaline, diatoms with wide ranging salinity tolerances, also present. This would suggest that despite the fact that Pattimore's Lagoon was no longer directly part of the Lake Conjola at this time, it was still a saline system dominated by marine waters. This could imply that during this period the lagoon was more connected to Lake Conjola than prior to the canal development, and presently, and/or that Lake Conjola was more connected to open ocean that it is currently. This may subsequently imply and that its more complete isolation, did not occur until more recently i.e., after 1000 yrs BP.

Subunit 2, from 1000-500 yrs BP, consisted of a layer of increasing silt and organic matter and large amounts of bioturbation. This suggests that Pattimore's Lagoon was a stable environment with increasingly lower energy levels, and possibly decreasing connection to Lake Conjola. The increase in organic matter suggests this period is marked by increased biological production. The diatom assemblage in this period was found to still be dominated by marine diatoms, and some euryhaline species. However, freshwater, fresh to brackish, and brackish to marine and marine to hypersaline tolerating diatoms were also observed. This would imply that the system was becoming more isolated from the ocean, and experiencing a more variable salinity environment, with periods of brackish and possibly freshwater conditions. However, this suggests that up to 500 years ago, Pattimore's Lagoon was still primarily experiencing salinities similar to the open ocean.

Subunit 1, from ~500 years ago to present, showed very high and increasing levels of silt and organic matter, peaking at nearly 18 % organic matter and 67% silt at 4 cm depth (about 180 years ago). This sub unit represents an increasingly organic and ecological productive, suggesting increasingly lower energy environment. This could be interrupted as further isolation from Lake Conjola or of Lake Conjola from the ocean. The last sample for diatom analysis represented the last ~50-100 years, period since the establishment of the canal estate. There were a very large number of diatoms present within this sample, most indicating fresh to brackish conditions, however diatoms indicative of brackish only conditions and of freshwater diatoms conditions were also present , along with marine, brackish to marine, and marine to hypersaline, and euryhaline species also present in smaller numbers. Overall this would indicate that the lagoon has been less saline in the very recent past, e.g., last 50-100 years by comparison with last 1000 years and is primarily a brackish system. The presence of marine and hypersaline species implies the lagoon at times experienced marine or hypersaline conditions. A reduced percentage of euryhaline diatom species may imply variability in salinity regimes may have decreased during this time period, as there were fewer diatoms with tolerance to variable salinity conditions. However this contrasts with the shear variety of diatoms found within this sample which indicates increased salinity variability by comparison to older units within the core.

The progression in diatom salinity tolerances can be seen in Figure 8.1. This figure shows the first two periods as marine environments with some euryhaline diatom species, this would have been a highly marine dominated system. As the lagoon evolves the existence of more variable diatom tolerances show an increase in salinity variation, and an overall decrease in salinity. This would suggest a decrease in connectivity with the ocean, and salinity now controlled by rainfall and evaporation patterns, more than just tidal exchange with the ocean. The last sample shows a highly variable brackish dominated system, indicating the trend of isolation from the ocean has continued.

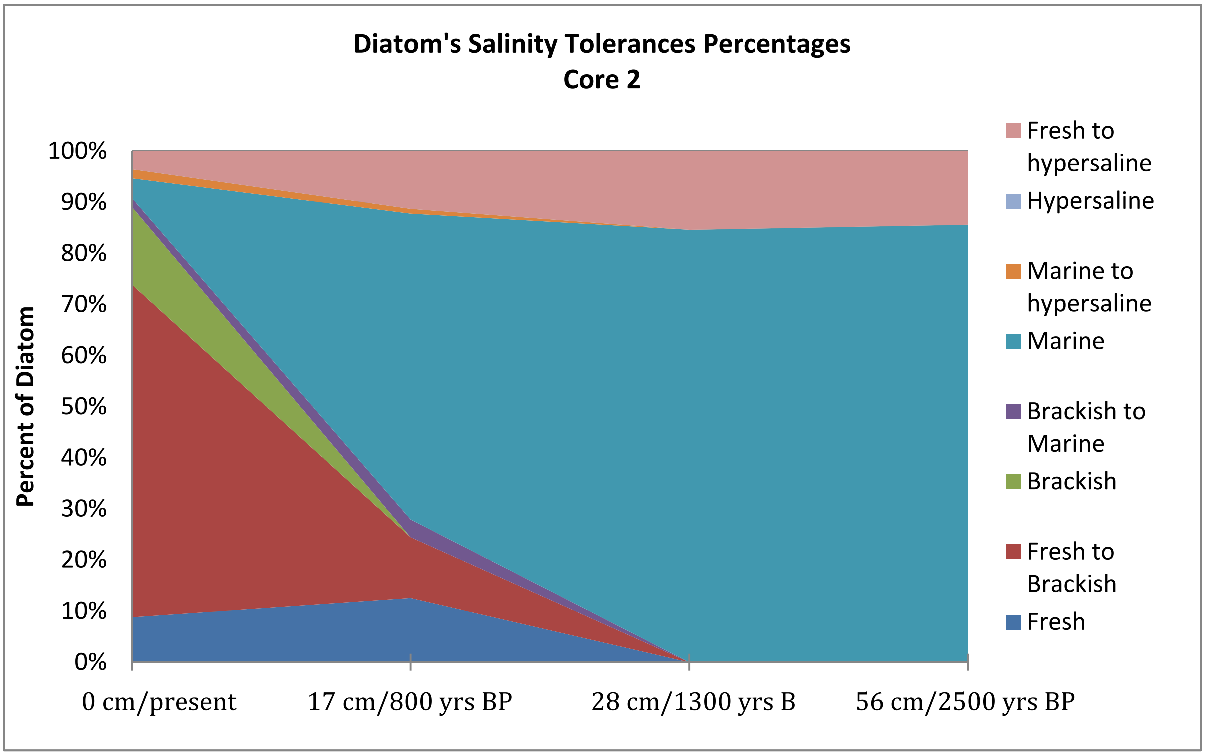


Figure 8.1: Diatom salinity tolerances found in samples from Core 2 in Pattimore's Lagoon.

Water quality data collected by Shoalhaven City Council from 2007 and 2012, demonstrated that Pattimore's Lagoon salinity ranged between 43.30 ppt (hypersaline) to 23.05 ppt (brackish). Indicating that Pattimore's Lagoon is a currently a highly variable environment in terms of it salinity.

These findings indicate that Pattimore's Lagoon became an isolated brackish system more recently than previously believed. Though there is a noticeable change in sedimentation which indicates that this system may not have been functioning as part of Lake Conjola from around 3500 years ago, the diatom analysis suggests salinity levels still remained fairly marine until ~1000 years BP. This suggests there was a greater connection to the ocean during this period than previously believed. The results also indicate that through time Pattimore's Lagoon was becoming more isolated from that Lake Conjola and/or the ocean, and was experiencing greater variations in salinity. Freshwater conditions may have been experienced briefly from time to time as indicated by the presence of freshwater diatoms and there was a gradual decrease in salinity. However, there is not enough evidence to suggest this system was naturally progressing to a freshwater system, though it could be concluded it was becoming more brackish.

The diatom analysis also found that that most of the freshwater diatoms within Sample 1 live in relatively acidic environments (John Tibby, personal communication 2012). Potential acid sulfate soils have been identified around Lake Conjola. This includes the bottom sediments of Pattimore's Lagoon has classed as having a high probability of acid sulfate formation within its bottom sediment, with lower probability for soils surrounding lake (Figure 8.2)(GHD, 2012). The level of possible acid sulfate soils around Pattimore's Lagoon combined with the high level of acid loving diatoms found in the sediment sample taken after the installation of the canal estate, suggest that during the construction of the channel some acid sulfate soils may be been disturbed.. Alternatively, drying or draining of the Pattimore's Lagoon during drought conditions may have led to acid sulfate formation. In any future works around Pattimore's Lagoon, the possibility of disturbing acid sulfate soils should be taken into account.

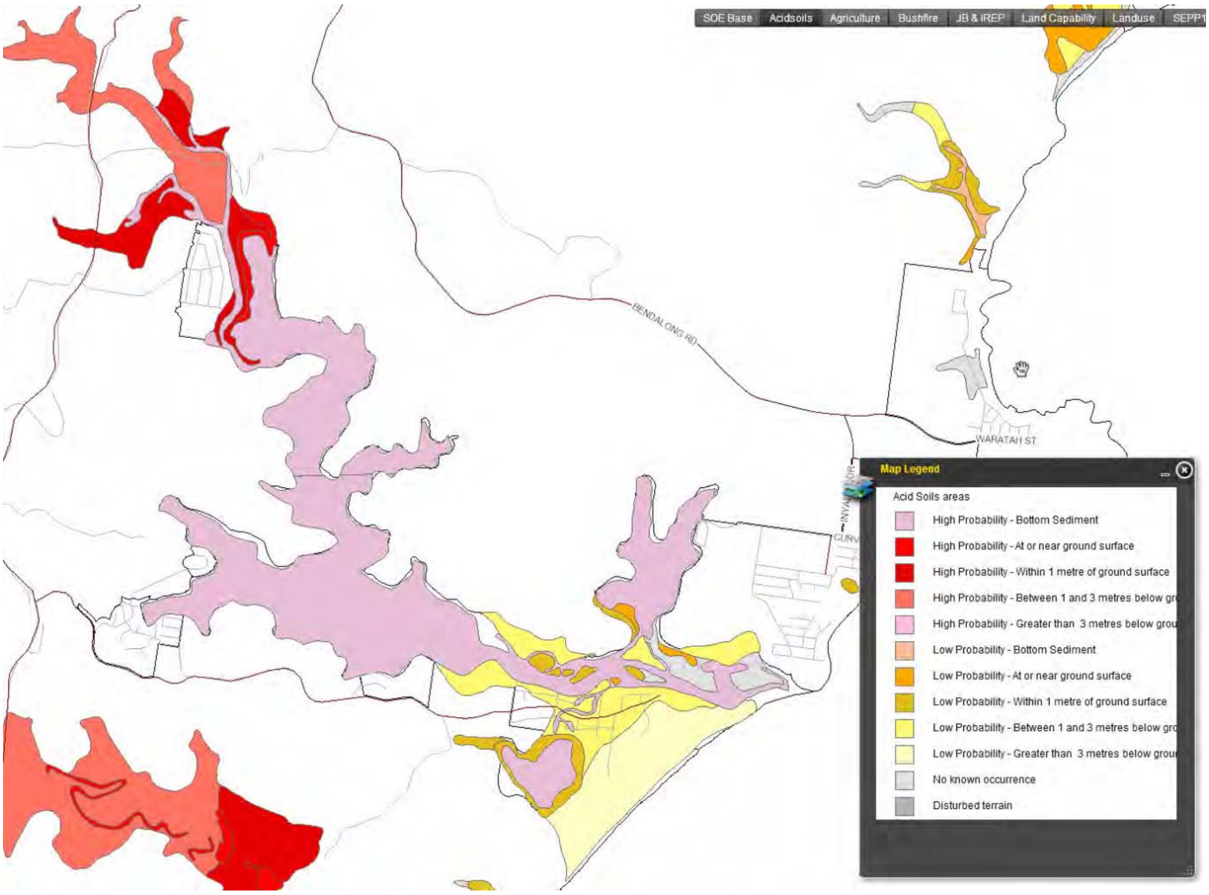


Figure 8.2: Map of potential acid sulfate soils around Lake Conjola (GHD, 2012).

8.4 Evidence for recent change

To effectively manage Pattimore's Lagoon, one must not only understand what the historic 'natural' state of the lagoon once was, but understand how the lagoon has changed, and what events have lead to the changes. This thesis investigated changes in Pattimore's Lagoon over the last 50 years through aerial photographic mapping of change. This method is by no ways inclusive of all potential changes in the lagoon, as changes in salinity, birdlife, or water quality cannot be determined. However, aerial photographs are the only data source available from before the canal estate was developed, and are the only source of regular data from the lagoon from which changes can be monitored.

The analysis showed the major changing factor in Pattimore's Lagoon was the development of a canal estate in the 1960-1980s. The development of the canal estate involved excavating drainage lines and a large canal leading to Lake Conjola. It has been believed that the canal estate increased Pattimore's Lagoon connection to Lake Conjola (Findlay, 1988, Shoalhaven City

Council, 1998, Shoalhaven Lakes & Estuaries Management Committe, 1996). The development of the canal also changed the entrance point into Pattimore's Lagoon from the northwest corner to the northeast.

The canal development first began to change Pattimore's Lagoon in the late 1960's when two areas were cleared, which altered the path of the channel. The old channel slowly filled in with vegetation and tree's until the area was completely vegetated by 2001. The diversion would have made many localized changes, but the extent of influence the change in channel entry point into the lagoon is undeterminable within the scope of this thesis.

The obvious indicator of the degree of change resulting from the development of the canal estate is a large delta which has built up at the new channel entrance. The delta has built at an average rate of 300 m^2 per year since at least 1972. At the original channel entrance, there was a relatively small delta, indicating that before the canal development, there was not enough tidal flow to bring significant amounts of sediment into Pattimore's Lagoon to construct a significant delta. The development of the sand delta at the new channel entrance indicates that the channel now has an increased flow of water into Pattimore's Lagoon. This would only be possible with increased tidal flow into the lagoon.

The weir, which was intended to reduce the tidal inflow into Pattimore's Lagoon, was installed in the early 1980's. However, it was observed that the sediment accumulation continued to increase at a similar rate through the 80's and 90s, indicating the there was still sufficient tidal discharge to deposit sediment into Pattimore's Lagoon, despite the presence of the weir. This implies that the weir failed to significantly restrict tidal connections to the lagoon.

Another significant change within Pattimore's Lagoon was the increase in mangroves around the lagoon. In 1988 two ~ 0.5 m mangroves were recorded in Pattimore's Lagoon (Findlay, 1988), (Figure 8.3). Thirty years later more than 40 mangroves are present, many of which are relatively large mature trees over 3 meters tall. The appearance of mangroves after the development of the canal estate, and their subsequent increase in abundance could imply that this change has been driven by construction of the canal estate, which allowed mangroves to enter the lagoon and flourish.

This development indicates that the altered connectivity lead to a change which allowed mangroves to colonise Pattimore's Lagoon.

Mangroves have adapted to deal with large amounts of salt, however, don't need salt to survive (Department of Environment and Heritage Protection, 2012). This would suggest that a change in salinity was not the major change in the lagoon, and instead mangroves responded to increases in tidal flushing (Breitfuss et al., 2003, Jones et al., 2004).

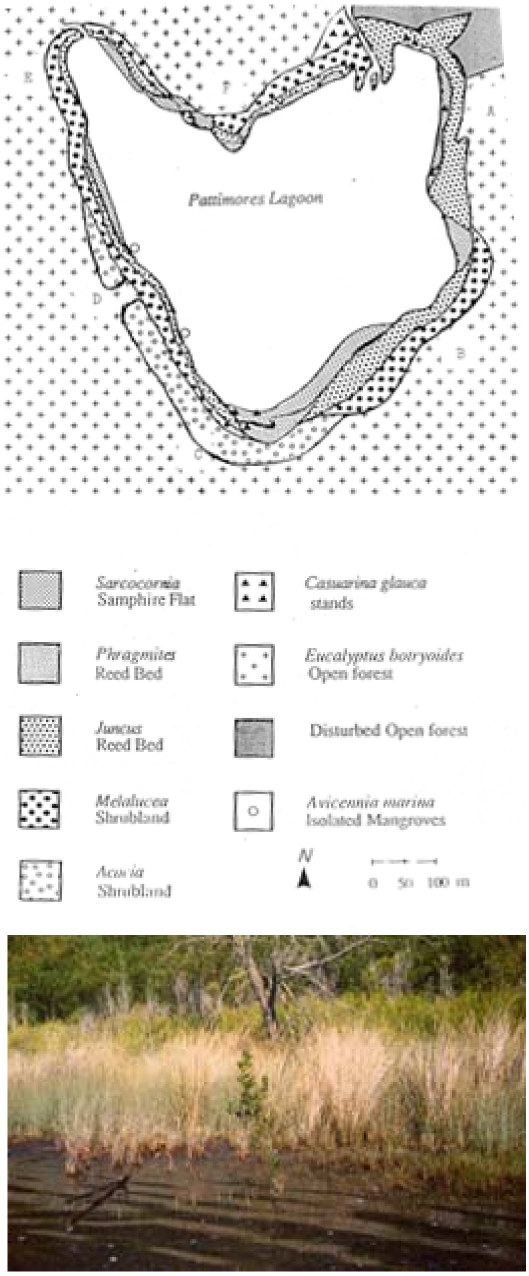


Figure 8.3: Above, vegetation map of Pattimore's Lagoon from Findlay 1988. This map shows the location of the only two mangroves in Pattimore's lagoon. Below, one of the two young pioneering Mangroves, photo take on 30 August, 1988. (Findlay, 1988).

Another factor which could have contributed to the increase in mangroves is increased nutrient levels and sedimentation rates from the canal estate (Saintilan and Williams, 1999). It has been suggested that increased nutrients and sediment loads from urbanization and dredging has led to the fertilization of salt marsh areas has led to an increase in mangroves and landward movement (Jones et al., 2004). There is also the possibility that mangroves could always survive within the lagoon, but the creek connecting Pattimore's Lagoon did not have sufficient tidal movement to transport propagules into Pattimore's Lagoon.

The increase in mangroves may be been isolated to Pattimore's Lagoon and instead may have occurred throughout Lake Conjola and its tributaries as the result of some larger scale change, such as changes in entrance conditions and therefore tidal flushing frequency. While an investigation into the history of mangrove numbers in Lake Conjola is beyond the scope of this thesis, more research into mangroves is necessary before conclusion into the causes of the increase can be made.

These observations indicate that the development of the canal estate did not only change the path of the natural channel, but seems likely to have increased the connection with Lake Conjola and altered the tidal regime in Pattimore's Lagoon. It can be concluded that since the start of the canal estate in 1964, Pattimore's Lagoon has experienced greater tidal flushing and more sediment deposition then was previously experienced, though in the long term , these changes might not new to the system.

8.5 Current state of Pattimore's Lagoon; tides, water quality, and vegetation

Understanding the natural, pre-European state of Pattimore's Lagoon, and the processes of change is vital to effective management. However the modern environment of the lagoon must be thoroughly understood if the system is to be effectively rehabilitated. This involves not only monitoring the current state of the lagoon, but also recognizing the major influencing factors and how those factors may vary in the future. To understand these issues, this thesis investigated the tidal environment of Pattimore's Lagoon, in context of Lake Conjola's entrance.

To understand the tidal regime within Pattimore's Lagoon, one must first understand Lake Conjola's tides. It was seen that the tidal regime is highly dependent on entrance conditions. Since 2005 Lake Conjola's entrance has varied from open, partially shoaled to near closure and has closed multiple times over the last 2 years. During this time the tides in Lake Conjola varied from averaging ~0.6 meters to ~ 0.35 m to ~0.05, respectively. In addition, the condition of the entrance of Lake Conjola, combined with the monthly lunar cycle resulted in changes in the temporal resolution of tidal connections in Pattimore's Lagoon. As the entrance shoaled, the tidal cycle changed from one dominated by diurnal tides to one dominated by spring tide pumping. Figure 8.4 shows that during open entrance conditions, the tidal environment is primarily dominated by 12 hour, diurnal tides. During shoaled conditions, the prevalence of 14 day spring tide pumping signal increases, and diurnal tides decrease. As the entrance nears closure, Lake Conjola becomes dominated by the 14 day spring tide pumping, while diurnal tides are no longer a major control.

This was pattern was clearly observed in Pattimore's Lagoon both within the tidal data collected during this study, and from 2008-2009, Figure 6.7-6.9. The variance in dominate tidal cycle makes this tidal pattern very complex. It also implies that to effectively manage the tidal environment of Pattimore's Lagoon, the management practices must work under diurnal tidal system as well as under 14 day spring tidal pumping cycles.

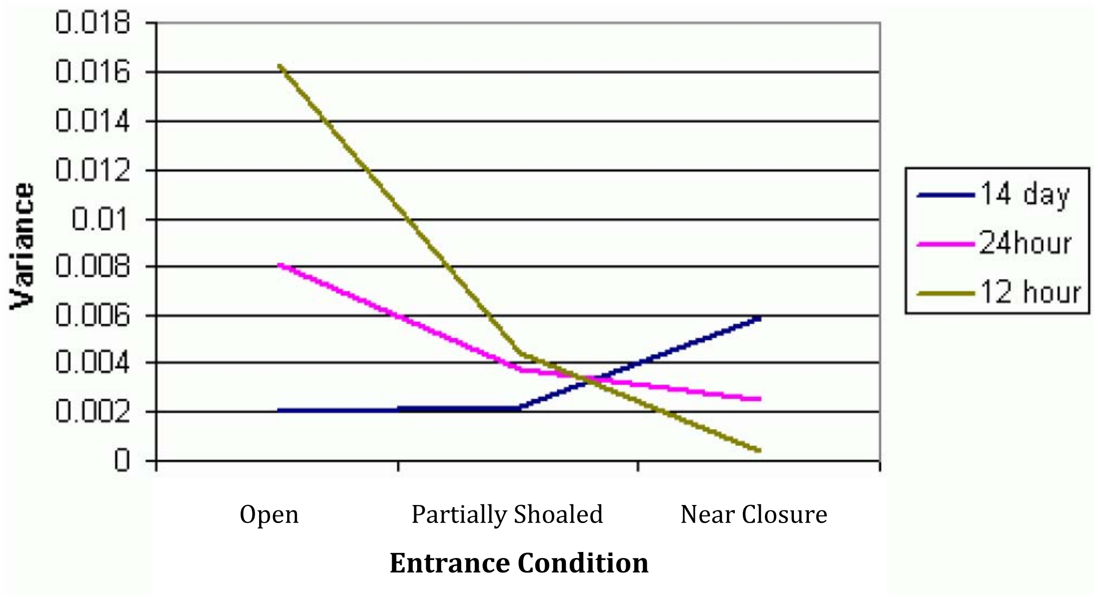


Figure 8.4: Plot of dominate tidal cycles seen with various entrance conditions, modified from Mclean and Hindwood 2011.

The level of tidal attenuation experienced in the channel leading to Pattimore's Lagoon was difficult to model with the data available. When making tidal attenuation models in Pattimore's lagoon the tidal height in Lake Conjola's entrance was so small that tidal attenuation appears minor (Figure 6.12) . However, during partially shoaled entrance conditions, when diurnal tidal heights in Lake Conjola were much larger, Berringer Lake experienced significant tidal attenuation (Figure 6.11) (Manly Hydraulics Laboratory, 2009). The much longer and narrower channel into Pattimore's lagoon suggests that Pattimore's Lagoon would experience more tidal attenuation than Berringer Lake, and so it is assumed that during larger tides in Lake Conjola, there would be larger tidal attenuation into Pattimore's Lagoon. The tidal attenuation graph did show that due to geomorphic constriction the channel experienced water levels ~0.05 m higher than those at Lake Conjola's entrance.

The weir was found to be effective at preventing tidal connections between Pattimore's Lagoon and Lake Conjola at water levels below 0.45 m AHD in the channel, (0.40 at Lake Conjola's entrance). As water levels increase above this level, tides begin to flow over this weir and into Pattimore's Lagoon. Using these findings, the level of connectivity through the various entrance conditions experienced can be modeled using water level and tidal heights in Lake Conjola. The three main entrance conditions and the resulting water levels and tidal heights can be used to model the frequency of Pattimore's Lagoon connection to Lake Conjola during each scenario.

During open entrance conditions, such as occurred between December 2005 and March 2006, the daily average water level was greater than 0.4 m AHD 5% of the time. This would indicate that Pattimore's Lagoon was fully connected to Lake Conjola only 5% of the time. However, high tides, may spill over the weir into Pattimore's Lagoon, raising the water level, as seen between November 15-19 (Figure 6.16). This would create a semi-connected environment and may occur daily or only during spring tides. In the absence of accurate tidal attenuation models, the water level and tidal heights at which this would occur cannot be modeled. Another constraining factor is it is that if the water level in Pattimore's Lagoon is not know, it cannot be know if water was able to flow over the weir and back out of the lagoon.

Under partially shoaled entrance conditions, such as seen from August to November 2007, the maximum daily average water level was 0.38 m AHD, so Pattimore's Lagoon was never fully connected to Lake Conjola. During this tidal variation was reduced. Though the level of high tide spill over cannot be accurately modeled, as discussed above, it can be assumed that during this period high tide spill over would occur less often than under open entrance conditions due to the reduced tidal heights and reduced water levels. Under these conditions Pattimore's Lagoon would be highly isolated from Lake Conjola. It was seen that during medium heights of M2 tidal constituent, which occur under partially shoaled entrance conditions, Pattimore's Lagoon experienced the highest salinity levels, and the only hypersaline conditions, Figure 6.18. It was also seen in Figure 6.19, as water levels decreased salinity increases. This suggests that when the lagoon is most isolated from Lake Conjola, is when it experiences the highest salinity concentrations.

During nearly closed entrance conditions, December 2009 to March 2010, the daily average water was above 0.40 m AHD 18% of the time. This period represents the time when Pattimore's Lagoon was most connected to Lake Conjola. It would also be seen that Pattimore's Lagoon could be connected for much longer periods of time that experienced in any other period. Tidal heights were much lower during this period, however the increased water levels could still lead a small amount of high tide spill over. This level of M2 tidal constituent represents the lowest salinity concentrations within the lagoon, Figure 6.18. It was also seen that during periods of higher water levels at Lake Conjola's entrance, salinity levels were lowest in Pattimore's Lagoon. As water levels are highest and M2 tidal constituents lowest during nearly entrance conditions, it can be assumed that Pattimore's Lagoon experiences its lowest salinity levels. This also implies that when Pattimore's during nearly or completely closed entrance conditions, when connection to Lake Conjola is greatest, Pattimore's Lagoon experiences the lowest salinity levels. This could imply that a greater separation of Pattimore's Lagoon from Lake Conjola could actually increase the salinity.

These findings demonstrate the complexity of Pattimore's Lagoon tidal signal. However they cannot be used to model the level of tidal connectivity as entrance conditions is not the only controlling factors influencing tidal heights and water levels. Rainfall patterns and ocean wave spillover also have major impacts on water levels, and so the level of connection would be impacted by weather variation such as ocean storms, rainfall/runoff and evaporation. Tidal heights are also influenced by the time of year and lunar cycle. Hypothetically, during period of drought, a closed entrance condition could experience lower water levels than during open ocean conditions, and Pattimore's Lagoon could become a completely isolated system. As such, longer term climate variability such as the El Nino Southern Oscillation, could also be expected to influence tidal connections.

8.5.1 Vegetation zonation and tidal inundation

Before any management of a system can be done, it is important to understand the impacts of current environment. As such, this thesis undertook vegetation transects to examine the affects various tidal regimes could have on the ecology of the lagoon. The vegetation transects were broken into distinct vegetation zones, and the average heights of each zone was found and used for analysis.

During the 3 different tidal periods in Pattimore's Lagoon vegetation experienced very different inundation patterns. During partially shoaled conditions, which were identified as the scenario in which Pattimore's Lagoon was the most isolated, the majority of the vegetation layers are not inundated regularly. As shoaling increased vegetation inundation becomes more frequently. During conditions in which the entrance is nearing closure vegetation was inundated more regularly. During the 5 month study period 2012, low lying grasses were inundated 100% in comparison to only 13% of the time in 2008. One interesting finding was, the average height of a pneumatophores is 20 cm, (Booker et al., 1998). Using that height, the pneumatophores would have been completely covered with water for 94% of the time over this 5 month study period, in comparison to 4% of the time during partially shoaled entrance conditions. As pneumatophores are the part of the roots with important for mangrove breathing, and it has been seen that when in poorly aerated soil mangroves can die when pneumatophores become covered, (Department of Environment and Heritage Protection, 2012), the effects of complete inundation over 94% of a 5 month periods could have major implications. However, on observation mangroves around Pattimore's Lagoon appeared to be in good health.

A more detailed study on the inundation tolerances and preferences of each species would need to be undertaken before any conclusions on vegetation health could be made, however this data shows the great variety of inundation regimes experienced by the vegetation, and suggests that this variety could pose great stress on some species and could benefit others. The presence of vegetation in these zones suggests that the vegetation has adapted to the patterns of inundation and variable salinities as discussed above. However, the presence of dying and dead *Meleleuca* and *Casuarinas* may imply that some vegetation types are not in equilibrium with the current inundation patterns, although more work would be required to confirm this.

Before any restoration works were undertaken, one would first need to understand what effects that change would have on the vegetation, which is at least to some degree, coping with this current inundation and salinity patterns.

8.6 Human induced change in Lake Conjola

Diatom evidence implies that Pattimore's Lagoon has always been at least partially connected to Lake Conjola, and as such, conditions in Lake Conjola significantly influence the environment in Pattimore's Lagoon. As part of an ICOLL system, Pattimore's Lagoon would have experienced a great range tidal regime, water levels, and salinity, as is still seen today.

The prevalence of ICOLL's along the southeast coast of Australia indicates that these types of estuary systems, with highly variable tidal, salinity, and water levels, are fairly common and natural. Partially connected wetlands and lagoon which rely on periodic inundation and other parts of an ICOLL cycle and been seen along this coast and around the world. As such, the current environment of Pattimore's Lagoon cannot be regarded as inherently unnatural.

It has been concluded in previous studies that the development of the canal estate has drastically altered Pattimore's Lagoon. However, this study has found that though it may have altered the level of connectivity experienced and consequently the tidal regime and salinity, these changes are not radically different to those previously experienced when the lagoon was in a more 'natural' state. The weir is effective at restricting connections at low water levels (<0.4m AHD), and may therefore be important for maintaining the current state of Pattimore's Lagoon. At higher water levels >0.4 m AHD, the condition of Lake Conjola's entrance is the most important factor effecting Pattimore's Lagoon, in combination with runoff and wave spill over. Entrance management therefore needs to be considered in managing Pattimore's Lagoon.

Globally, mean sea level rise have risen 21 cm since 1880 (NSW Chief Scientist and Engineer, 2012). These changes could potentially have affected the level of connectivity experienced by within Pattimore's Lagoon by increasing the mean water levels in Lake Conjola. The impact of this, was however, beyond the scope of this thesis.

8.7 Future changes in Pattimore's Lagoon

The Intergovernmental Panel on Climate Change (IPCC) has projected global surface warming of up to 4 °C in by 2100 (Intergovernmental Panel on Climate Change, 2007). Climate change will influence mean sea level, wave climate, and rainfall behavior and thus affect the condition, structure and functioning of NSW estuaries (Haines and Thom, 2007, Intergovernmental Panel on Climate Change, 2007) Along the southeast coast of Australia sea levels are predicted to rise another 40 cm by 2050 and 90 cm by 2100 (NSW Chief Scientist and Engineer, 2012).

Climate change is predicted to influence entrance processes by increasing mean sea level which is predicted to moving the entrance of the berm upwards and landwards (Haines and Thom, 2007, Hanslow et al., 2000), Figure 8.5. Changes in wave climate are also predicted to strongly influence opening and closing cycles of ICOLLs. The predicted increase in southeasterly waves may cause some small scale beach erosion and net accretion at the northern ends of beaches. For estuary entrances at the northern ends of beaches, such as Lake Conjola, this is predicted to result in a net growth of the entrance berm as well as increased water level behind the berm (Haines and Thom, 2007). This could result in higher water levels in Lake Conjola and a greater increase than just rise in sea rise. This would result in a much greater connection between Pattimore's Lagoon and Lake Conjola.

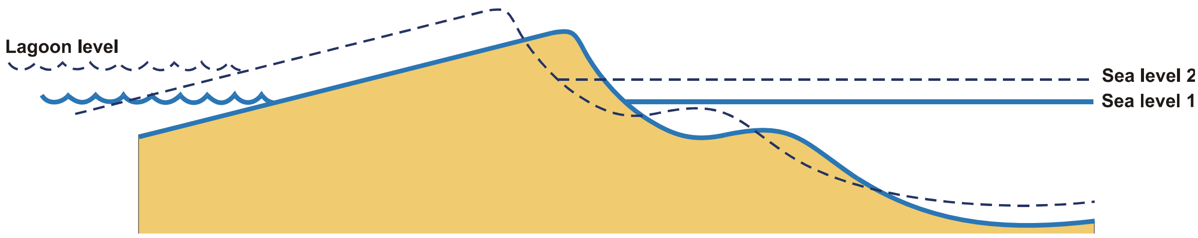


Figure 8.5: Sea level rise resulting in a upward and landward translation of the berm crest resulting in higher lagoon levels (Hanslow et al., 2000).

Chapter 9. Conclusion and Recommandations

9.1 Conclusion

The aim of this thesis was to increase the understanding of Pattimore's Lagoon to assist management in increase environmental outcomes within this highly modified system. This was undertaken through four objectives,

- Determine the natural state of Pattimore's Lagoon environment before European settlement.
- Determine how the Pattimore's Lagoon has changes due to the construction of the canal estate.
- Determine what the current state of Pattimore's lagoon is in regards to tidal regime, salinity, and vegetation.
- Determine the major influences on Pattimore's Lagoon and how they vary over time.

The first objective of this study used sediment cores to model historic evolution and salinity. It was found that the palaeo-evolution of Pattimore's follows commonly accepted models of estuary evolution on the southeast coast of Australia. Pattimore's Lagoon would have evolved as sea level rose flooding the river valley and subsequently stabilized, allowing the estuary to mature and infill. As the estuary infilled the lagoon environment we see today would have gradually became a more isolated due to sediment deposition.

The investigation of the salinity regimes during this lagoonal period found that this system has been dominated by marine waters for longer than previously believed and only recently has became a predominantly brackish system. As the lagoon matured, it evolved from an environment completely dominated by marine waters, to primarily marine with freshwater, brackish, and hypersaline periods. Currently the lagoon is a dominantly brackish water system but fluctuates from fresh to hypersaline. There is some evidence to suggest that the connection to Lake Conjola may actually decrease the salinity in the lagoon during periods of nearly closed entrance conditions and high water levels.

The second objective was completed through the analysis of aerial photographs of Pattimore's Lagoon since 1950 and past studies of the Lagoon. The increased sedimentation and colonization of mangroves have confirmed the belief that the installation of a canal estate from the 1960-1980 has increase the tidal flow into the lagoon. This investigation also proved that the installation of the weir in the early 1980, which collapsed in the late 1980, has not succeed in restoring the lagoon to its natural salinity regime, as after the weir was installed sedimentation and mangrove colonization continued. Factors such as vegetation and water quality could not be assess using aerial photographs, however change in these areas during this time period is very likely.

The third objective found that currently Pattimore's Lagoon's tidal environment is highly variable and primarily controlled by water level and the tide heights, both of which are heavily influenced by Lake Conjola's entrance conditions. It was seen that as the under different entrance conditions, Pattimore's Lagoon varies between three primary states of connectivity and tidal influence;

- No connection during periods of low water levels and small to no tides –often experienced during partially shoaled entrance conditions.
- Complete connection during periods of high water levels in Lake Conjola and Pattimore's Lagoon. This period is primarily experienced during nearly closed entrance conditions and accompanied by very small or no tides.
- Partial connection during periods when mean water levels Lake Conjola are low but tides are height enough to overtop the weir. During this period often high tides spill over the weir but due to low water levels in Pattimore's Lagoon often cannot flow back out during low tides, causing the lagoon to gradually fill with water. This is mostly experienced during open entrance conditions.

The investigation into vegetation inundation showed that almost all of the vegetation layers experienced highly variable frequencies and duration of inundation during various entrance condition. Some vegetation, mainly isolated casuarinas, appeared to be in poor health, however the majority of the system appeared to be adapted to survive the different inundation patterns and some research suggest may benefit from periodic inundation.

Lastly, it was found that the main control was Lake Conjola's entrance condition, as it influences tidal heights and the water level, and thus connectivity and salinity in Pattimore's Lagoon. Other factors included rainfall patterns and ocean wave spill over. It was also found that the potential impacts of climate change could significantly alter these controlling factors, and should be take into account during future planning and management.

In context of restoring Pattimore's Lagoon to its natural regime, it was concluded that the lagoon is not behaving entirely unnaturally, and though it is a variable and complex system, it is thought to be behaving relatively similarly to what would have been experienced previously.

However, careful consideration should be taken before making any changes which could alter the lagoons environment again.

9.2 Recommendations

Key recommendations for future research and management of Pattimore's Lagoon include;

-Investigate the potential impacts on the recent sea level rise seen along the NSW coast over the last century and its potential impacts of future sea level rise on Lake Conjola's water level and thus the connectivity of Pattimore's Lagoon.

-Further study into each vegetation species individual ecological tolerance for height and duration of inundation to see which periods of time are most suitable, and which are most ecologically stressing.

- Further study into the length of the pneumatophores on the mangrove species, it has been found that mangrove pneumatophores vary in length in relation to the tidal variation, as they need to be exposed to the air regularly. In an environment such as Pattimore's with long periods of high inundation, you would expect to see longer pneumatophores than average. This could be used to investigate how the mangroves are coping with the long periods to entrance closure.

-Further research into mangrove colonization within Lake Conjola to see if there has also been an increase in mangroves throughout the entire estuary and not only Pattimore's lagoon.

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Appendix 1 Core 1

Samples

1
2
3
4
5
6
7

Depth (cm)	Description	Bioturbation	Sorting and grain size	Colour	Mottles
0-5	**Grey sand layer -lightens and coarsens downwards**	**0%**	**Well sorted Angular**	**5Y 4/1 grey**	**Slight discoloured areas - one 1cm by 3cm darker mottle with undistinct edges**
5-8	Grey sand -lightens downwards	<1% very small white shell fragments	Well sorted Angular	5Y 6/1 grey	Small <5cm faint darker mottles
8-14	Light grey sands with darker streaks throughout	May be bioturbation mixing	Well sorted very sandy Angular	5Y 7/1 light grey -with streaks 5Y 5/1 grey	**Dark blackish and greyish brown mottles and streaks. May be from burrowing -undistinct boundaries ~.3m wide and > 1cm long**
14-17	**Light white sands**	**May be traces of burrows**	**Large well sorted angular grains**	**5Y 7/1 light grey**	**Dark brown grey mottles ~ .5cm by .5cm -very dark organic piece ~0.2cm**
17-22	**More purple grey sand with darkens downwards -cracks and voids present**	**Streak of light sand and brown most likely a burrow**	**Large angular sand grains**	**N/5 grey gley**	**One small ~0.2cm mud mottle with distinct edges**
22-56	Dark grey sandy loam with mixed colouration	0%	Smaller more rounded sand grains	5Y 4/1 dark grey	Very indistinct silty mottles darker colours from 0.1cm -1cm
56-75	Dark grey sandy 1cm with sparse shells and silty mottles	~5% soft white flat shells -some small ~0.8 soft curly shell fragments	Well sorted Semi rounded	5Y 4/1 dark grey	Light sandy mottles ~0.4cm -some indistinct silty mottles ~0.2cm by ~0.5cm

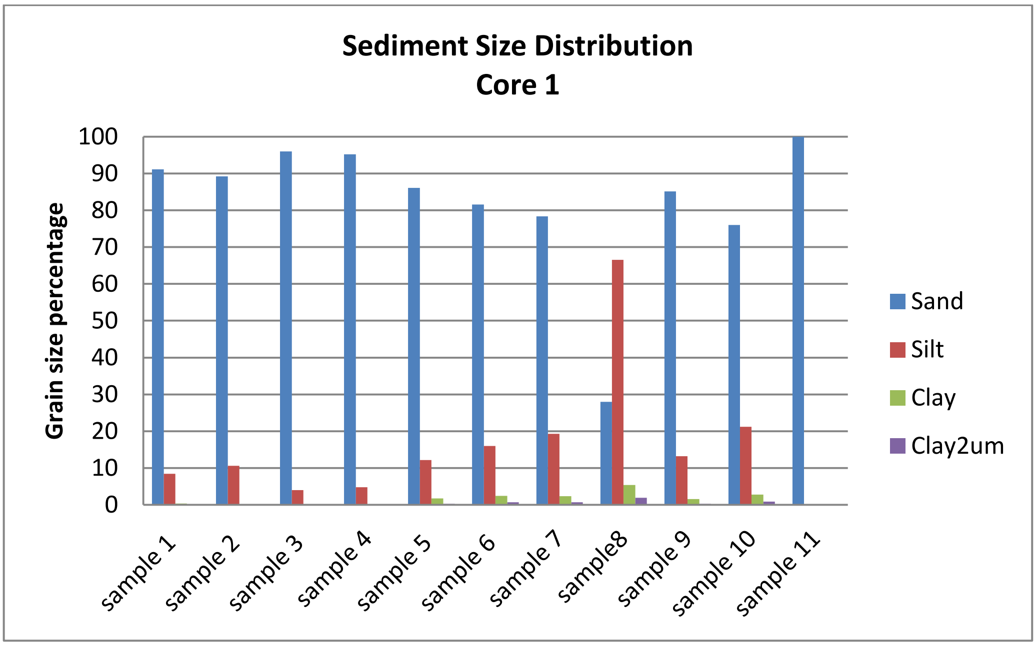
8

75-79	Grey sand High shell density -1 large 0.5cm pebble	-50% shells -twirly shells 4cm -pinck curled shells -2cm -flat white shells ~3cm	Well sorted semi rounded	5Y 4/1 dark grey	
79-85	dark grey sandy loam with fewer shells	~30% white flat shells fragments very soft	Well sorted semi-rounded	5Y 4/1 dark grey	Some mixed colouration
85-94	Dark grey sandy loam with fewer shells	10% shells -3cm twirly shells -a few fragments of flat white shessl	Well sorted semi rounded	5Y 4/1 dark grey	Darker silty mottles with very indistinct boundaries
94-99	Slanted ~2 cm dark brown silty layer	Roots anad plant fragments present	Very fine grained ~80% silt well sorted	5Y R 3/1 very dark grey	
99-102	**Loam layer of dark brown silt mixed with light grey sand** **-lots of shells**	**~30% Cream coloured shell fragments**	**Poorly sorted**	**5 Y 3/1 very dark grey**	
102-130	**Dark grey sand with shells and mottles**	**~10% shells** **-1 large 3 cm twirly shells fragments** **-read twirly fragments ~1cm** **-pink twirl with a white top ~1cm** **-white fragments**		**5Y 5/1 grey**	**Some very faint finer grained brownish mottles**
130-154	**Light grey sandlightening downwards**	**~5% shells** **-white shell fragments** **-1cm _____**	**Poorly sorted angular sand grains**	**5Y 5/1 grey**	**Some very faint finer grained brownish mottles**

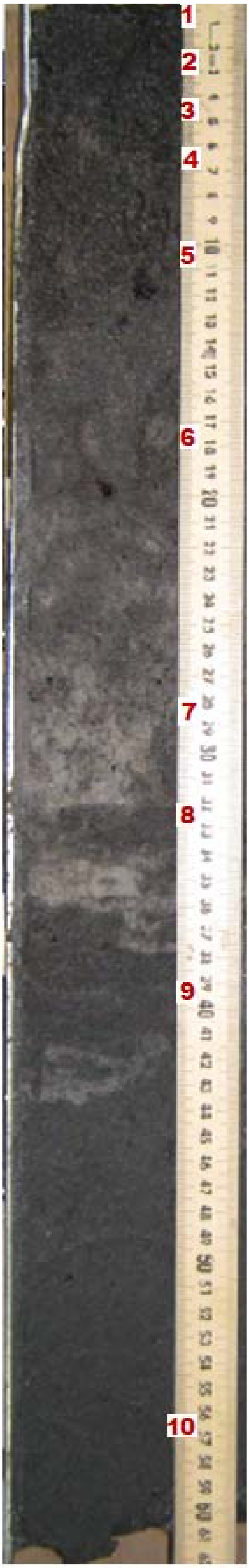
9

10

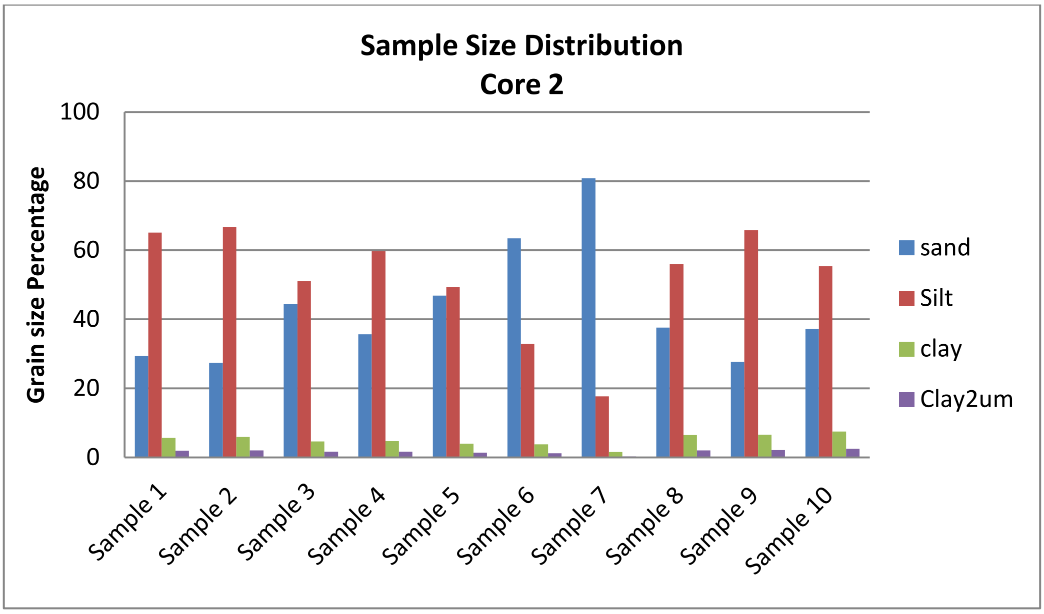
						
	154-217	**Light grey large grained sand lightening downwards**	**<1% shells -1 twirly ~3cm long**	**Poorly sorted angular sand grains**	**5Y 5/1 grey**	**0.1cm streak running from start to 177**

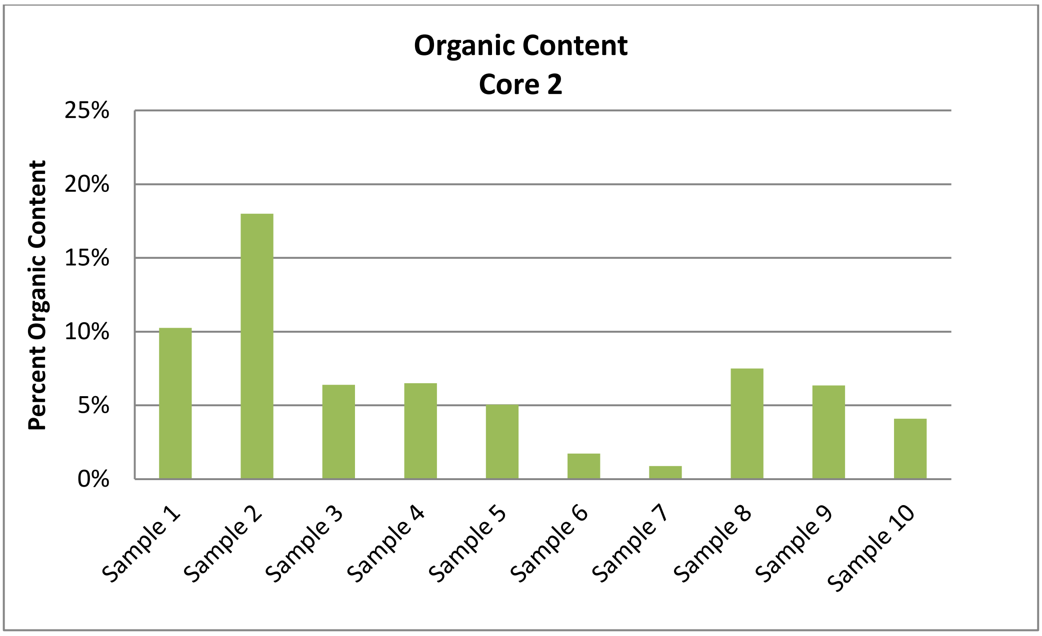

Sediment Size Distribution
Core 1
Grain size percentage
100
90
80
70
60
50
40
30
20
10
0
sample 1
sample 2
sample 3
sample 4
sample 5
sample 6
sample 7
sample8
sample 9
sample 10
sample 11
Sand
Silt
Clay
Clay2um

Samples



Depth (cm)	Description	Bioturbation	Sorting and grain size	Colour	Mottles
0-3	**muddy Very organic less compact**	**Roots and bioturbation ~30%**	**Moderate sorting 28% sand 65% silt 5% clay**	**2.5/10Y Greenish/ brownish black**	**Type M. Few very coarse with clear boundaries and grey colour**
3-6	very muddy with high organic matter with some mottles of sand less compact	Very bioturbated, with roots and carbon and some leaves ~40%	Poorly sorted 44% sand 51% silt 6% clay	2.5/10Y with sand mottles of 4/10Y	Type M. Common very coarse with clear boundaries and grey colour
6-10	Muddy fine grained less compact coarse macropore ~1cm in diameter. Most likely a burrow	Very bioturbated- visible roots, leaves, 1mm carbon/ wood pieces ~30%	Poorly sorted 35% sand 60% silt 5% clay	2.5/10Y very dark but more brownish	
10-20	**Fine mud w/ 10% sand mottles and 5% brown mud mottles Fairly compact**	**Lots of wood and visible roots Very bioturbated ~20%**	**Poorly sorted 45-63% sand 50-32% silt 4% clay**	**3/5GY with More greyish with 4/10Y sandy mottles**	**Type M. Many very coarse with distinct boundaries and sand grey colour. Also a very course brown mud with a sand mottle inside**
20-31	**Grey silt and light sand with increasing sandiness downwards compact**	**Lots of roots and heavily bioturbated with little black bits of carbon ~10%**	**Very poorly sorted 80% sand 17% silt 2% clay**	**Starts at 4/5G and goes to light sand of 6/10Y**	**Type X. Probably from burrowing. Many mixing of light sand with dark organic rick muds with fine to very coarse colour changes**
31-33	Dark organic silty layer compact	Still roots & bioturbation mixing sand ~20%	Poorly sorted 37% sand 56% silt 2% clay	2.5/10Y	
33-35	Sand sheet with some larger grains over on uneven surface compact fine void ~ 1mm	Roots and organic flecks present ~10%	Very poorly sorted	Very light 6/10Y	Type X mixing of light sand and dark organic rich muds
35-38	Rich in organic matter compact	Air pockets or burrows present roots bits of carbon ~20%	Moderate sorting	2.5/5GY Dark brownie grey layer	
38	~2mm sandy layer	Bioturbated with a small burrow		2.5/10GY	
38-40.5	Organic rich dark grey silty layer compact very few fine voids	Less signs of bioturbation ~20%	Moderate sorting 27% sand 65% silt 7% clay	2.5/10GY	
40.5-42.5	Sandy layer with strips of darker organic matter Uneven erosion surfaces	Roots present ~20%	Very poor sorting	5/10Y with strips of 3/N	Type x. Very common mixing of darke brown/black organic muds with light sand layers. As well as dark organic flecs
42.5-60	**Large silty layer with some sand More compact Very few fine voids**	**Roots and bioturbation some ~1mm organic pieces ~15%**	**Well sorted 37% sand 55% silt 7% clay**	**2.5/10GY Very dark grey Gradually darker as you move down**	


Sample Size Distribution
Core 2
Grain size Percentage
100
80
60
40
20
0
sand
Silt
clay
Clay2um
Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6
Sample 7
Sample 8
Sample 9
Sample 10


Organic Content
Core 2
Percent Organic Content
25%
20%
15%
10%
5%
0%
Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Sample 6
Sample 7
Sample 8
Sample 9
Sample 10

Appendix 1 Core 3

Depth (cm)	Description	Bioturbation	Sorting and grain size	Colour	Mottles
0-3	**-highly organic -loam**	**0%**	**Well sorted**	**5Y 3/2 Very olive grey**	
3-8.5	-highly organic -loam with more sand than above	~1% roots and small shell fragments	~50% sand	5Y 4/2 olive grey	
8.5-10	-highly organic -loam with more sand than above	0%	Poorly sorted	Dark olive grey with light mottles -5Y 4/2	-Very Mottled -unclear boundaries -light sand sith dark silt
10-18	**Increasing sand content -grey sandy loam**	**Very few roots**	**Poorly sorted**	**5Y 3/1 very dark grey**	**Grey base with 2 different colour mottles and streaks with unclear boundaries -<1 -5mm. -darker siltier mottles -light white sand with dark silt layers**
18-20	**Grey loam**	**0%**	**Moderate sorted**	**5Y 3/1 very Dark grey**	
20-28	Sandy loam	~2% roots	Well sorted	5Y 3/1 very dark grey	10% mottles very small <1mm dark grey mottles and streaks
28-42	Sandy loam	~1%, might be a burrow	Large sand grains	5Y 3/1 very dark grey	1 distinct type M mottle 1cm by 4 cm dark silt mottle -5% less distinct silty mottles
42-43	Dark strip		Moderate sorting	5Y 2/1 black	
43-53	Sandy loam with decreasing sand content downwards		Moderate sorting	5Y 4/1 dark grey	
53-76	Dark sandy loam ~2% voids 2mm by 2mm	10% broken shells, very soft white crumbly fragments up to 2 cm		5Y 4/1 dark grey	1 distinct dark mottle 1cm by 1cm

						
	76-113	Dark grey loam with increasing silt downwards -lots of small <1cm voids ~5% -dark strip at 105cm	~10 % shells fragments up to 2cm A ~1cm white twirly shell Some read textured shells (1cm by 1cm)		5Y 4/1	~2% undistincit darker mottles
	113-160	**Dark grey silty loam with increasing sand downwards** **-lots of voids** **-charcoal layer at 153-154 with little fragments**	**-30% shells** **-1cm curly red ones throughout** **-little fractured white ones throughtout** **-1 5cm long bit_______ at 124cm** **-more shells as you move downwards. With large flat shells starting to become common** **-1, 1cm shinny curly shell near bottom.**		**5Y 4/2 olive grey**	

						
	160 – 162	**Light marine sand layer with increasing sand downwards**	**~40% of shell fragments, grey and white flat shell fragments**	**Larger sand grains Well sorted**	**5Y 4/2 olive grey**	
	162 - 200	**Light marine sand layer with increasing sand downwards**	**Less shells as you move down, starting at about 5% shells to ~1 % at bottom Flat grey shells With some up to 3 cm -long spiral shells**		**5Y 5/1 grey**	**Darker silt mottles from 1mm to 1 cm Some darker grains**

Appendix 1 Core 4

Depth (cm)	Description	Bioturbation	Sorting and grain size	Colour	Mottles
0-10.5	-light grey sand	<5% signs of burrowing	Mostly sand	5Y 7/1 light grey	10% mottles -small ~.5cm silty brown mottles with indistinct boundaries -1 large dark sandy mottle~ 3cm by 3cm
10.5-18	Very mixed layer -left side light sand with mottles same as above -middle layer a darker sandier region withdark silt -right side grey sandy region with larger grains	~1% very small shell fragments	> 50% sand	5Y 5/1 grey	1 distinct greenish grey mottle ~ 1 cm by 1cm , still sandy -some oval mottles on left side same as above --3 indistinct greenish grey mottles ~ 0.2cm along left side
18-43	Dark grey sandy loam with larger slity mottles	0%	~ 50% sand	5 Y 4/1 dark grey	~10% undefined mottles could be type X darker coloured from 1cm by 1cm to <0.5mm
43-55	Dark grey sandy loam with lager silty mottles and with a big soft shell	1 large 3cm _____ very soft cream coloured	~50% sand	5Y 3/1 very dark grey	Some uneven colouring but not distinct mottles
55-72	Grey sand layer full of shells -lightening and increasing downwards	>5 3cm long twirly shells -brown with with tips, -small fragments of broken white sand very soft	~50% sand	5Y 3/1 very Dark grey	

	72-93	Fine grained muds layered with grey sand with some dark organic marterial and pieces in a 0.1 cm strip	~small organic wood or root pieces -some burrows mixing but almost no shell fragments	Poorly sorted silt layer sand layer	5Y 3/2 very dark grey	
	93-108	Light grey sandy layer with increasing sand and shells downwards	Small soft white shell fragments, grey flat shell fragments	Mostly sand	5Y 4/2 dark grey	Some colour variations from biological mixing
	108-128	Light grey sand layer lightening downwards	20% Shell -twirly 3cm - curly ones 2cm -smooth curly ones -flat white shells appearing towards bottom	Well sorting, mostly sand	5Y 5/1 grey	Lots of biological mixing
	128-136	Light grey sand with sparcer shells Lightening downwards	5% shells Flat white shells at the top ~2cm and some fragments	Moderate sorting Mostly sand	5Y 6/1 grey	
	136-158	Light grey sand lightening downwards sparser shells	<5% shells -purple twirly -pinks shells 1 cm -white curled shell ~1 cm -flat white shell fragments		5Y 6/1 grey	1 distinct dark mottle 1cm by 1cm

						
	158-171	Large grained light grey sand <1% dark black grains of sand	5% shells -2cm whitish blue flat shell fragments -1 large 6cm long twirly shell	Well sorted	5Y 6/1 grey	
	171-196	Very light grey large grained sand with sparse shells	<10% shells But many species present	Well sorted large sand grains with one large bluish pebble	5Y 6/1 grey	
	196-208	Very light large grained sand	No shells	Well sorted large grained sand	5Y 6/1	

Appendix 2

AAR DATING

Sample number	Lab Number	Species	Notes	Initial Mass	Volume of	Mass after	Volume of	Time in ov	Sub sample	Frees	Volum	Date run	Frees run
PC 68cm	9853a1	Batilleria?	x 2 sub-sam	175.7	579.8	132.4	2648	9.45 1/8	50	Yes	50	2.8.12	Yes
	9853a2			292.9	966.6	202.4	4048	9.45 1/8	50	Yes	50	2.8.12	Yes
PC 78 cm	9853b1		x 2 sub-sam	218.9	722.4	148.1	2962	9.45 1/8	50	Yes	50	2.8.12	Yes
	9853b2			225.3	743.5	163	3260	9.45 1/8	50	Yes	50	2.8.12	Yes
PC 127 cm	9853c1		x 2 sub-sam	173	570.9	117.2	2344	9.45 1/8	50	Yes	50	2.8.12	Yes
	9853c2			183.2	604.6	115.1	2302	9.45 1/8	50	Yes	50	2.8.12	Yes
PC 135 cm	9853d1		x 2 sub-sam	288.3	951.4	196.6	3932	9.45 1/8	50	Yes	50	2.8.12	Yes
	9853d2			230.8	761.6	163.9	3278	9.45 1/8	50	Yes	50	2.8.12	Yes
PC 189 cm	9853 e1		x 2 sub-sam	221.3	730.2	150.3	3002	9.45 1/8	50	Yes	50	2.8.12	Yes
	9853 e2			160.9	530.9	103.6	2072	9.45 1/8	50	Yes	50	2.8.12	Yes

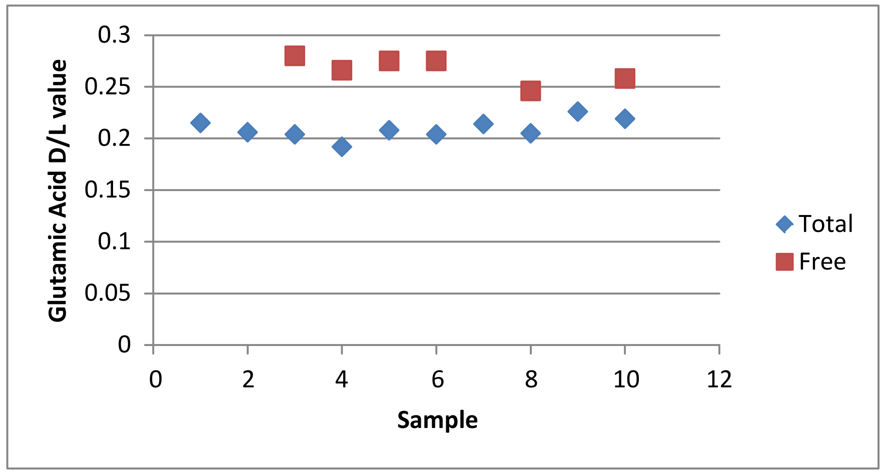
	ASP A	ASP H	GLU A	GLU H	SER A	SER H	ALA A	ALA H	VAL A	VAL H	PHE A	PHE H	ILE A	ILE H	LEU A	LEU H
9853a1	0.642	0.664	0.215	0.2125	0.688	0.622	0.314	0.357	0.109	0.1	0.43	0.377	0.14	0.116	0.229	0.248
9853a2	0.638	0.658	0.206	0.206	0.616	0.609	0.306	0.345	0.103	0.1	0.39	0.349	0.128	0.108	0.216	0.233
9853b1	0.553	0.538	0.204	0.1984	0.631	0.307	0.279	0.305	0.105	0.1	0.37	0.323	0.157	0.108	0.186	0.201
9853b2	0.518	0.533	0.192	0.1911	0.627	0.625	0.265	0.295	0.102	0.09	0.34	0.304	0.122	0.102	0.176	0.191
9853c1	0.62	0.638	0.208	0.206	0.64	0.638	0.32	0.355	0.114	0.11	0.39	0.354	0.161	0.123	0.212	0.227
9853c2	0.693	0.715	0.204	0.2019	0.69	0.672	0.31	0.367	0.112	0.11	0.44	0.379	0.142	0.12	0.227	0.24
9853d1	0.574	0.59	0.214	0.2128	0.686	0.689	0.315	0.35	0.117	0.12	0.42	0.382	0.155	0.132	0.228	0.243
9853d2	0.765	0.789	0.205	0.2024	0.857	0.844	0.356	0.428	0.099	0.1	0.5	0.43	0.143	0.118	0.27	0.286
9853 e1	0.698	0.721	0.226	0.223	0.615	0.62	0.329	0.381	0.118	0.12	0.42	0.386	0.153	0.13	0.238	0.253
9853 e2	0.804	0.83	0.219	0.2157	0.877	0.831	0.492	0.462	0.109	0.11	0.49	0.423	0.16	0.127	0.283	0.297
Mean	**0.651**	**0.668**	**0.209**	**0.207**	**0.693**	**0.646**	**0.329**	**0.365**	**0.109**	**####**	**####**	**0.371**	**0.146**	**0.118**	**0.227**	**0.242**
Std dev	**0.091**	**0.099**	**0.010**	**0.009**	**0.097**	**0.147**	**0.063**	**0.050**	**0.006**	**####**	**####**	**0.040**	**0.013**	**0.010**	**0.033**	**0.033**
CV	**14.015**	**14.822**	**4.544**	**4.473**	**13.935**	**22.738**	**19.055**	**13.846**	**5.969**	**####**	**####**	**10.714**	**9.220**	**8.485**	**14.522**	**13.579**

(Free amino ac	ASP A	ASP H	GLU A	GLU H	SER A	SER H	ALA A	ALA H	VAL A	VAL H	PHE A	PHE H	ILE A	ILE H	LEU A	LEU H
9853a1F	Wobbly baseline															
9853a2F	Wobbly baseline															
9853b1F	0.752	0.772	0.28	0.2785	1.065	0.808	0.461	0.489	0.149	0.13	0.74	0.671	0.233	0.173	0.422	0.458
8753b2F	0.755	0.778	0.266	0.2718	1.039	0.79	0.472	0.496	0.17	0.13	0.76	0.693	0.235	0.171	0.337	0.436
9853c1F	0.839	0.863	0.275	0.2771	1.143	0.891	0.532	0.548	0.163	0.14	0.79	0.704	0.232	0.179	0.405	0.467
9853c2F	0.873	0.901	0.275	0.273	0.96	0.951	0.554	0.569	0.156	0.14	0.76	0.679	0.221	0.169	0.344	0.436
9853d1F	Wobbly baseline															
9853d2F	0.888	0.922	0.246	0.257	1.065	1.045	0.578	0.586	0.118	0.11	0.73	0.65	0.19	0.15	0.425	0.462
9853e1F	Wobbly baseline															
9853e2F	0.907	0.941	0.258	0.2658	1.103	1.033	0.552	0.588	0.114	0.11	0.71	0.637	0.191	0.149	0.415	0.441
Mean	**0.836**	**0.863**	**0.267**	**0.271**	**1.063**	**0.920**	**0.525**	**0.546**	**0.145**	**####**	**####**	**0.672**	**0.217**	**0.165**	**0.391**	**0.450**
Std dev	**0.067**	**0.073**	**0.013**	**0.008**	**0.062**	**0.109**	**0.048**	**0.044**	**0.024**	**####**	**####**	**0.025**	**0.021**	**0.013**	**0.040**	**0.014**
CV	**8.070**	**8.440**	**4.800**	**2.956**	**5.831**	**11.875**	**9.071**	**8.044**	**16.250**	**####**	**####**	**3.776**	**9.723**	**7.624**	**10.230**	**3.095**

Appendix 2

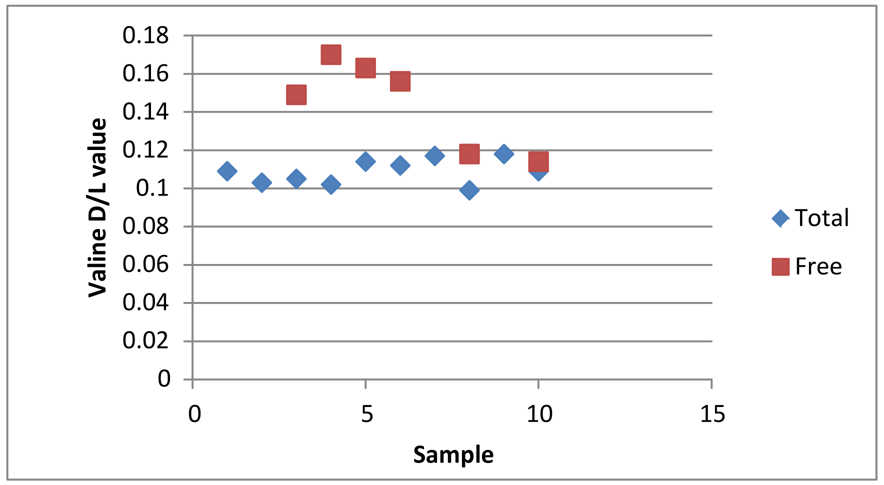
Plot of total and free amino acids from each sample for Glutamic

GLU	Total	Free
9853a1	0.215	
9853a2	0.206	
9853b1	0.204	0.28
9853b2	0.192	0.266
9853c1	0.208	0.275
9853c2	0.204	0.275
9853d1	0.214	
9853d2	0.205	0.246
9853 e1	0.226	
9853 e2	0.219	0.258



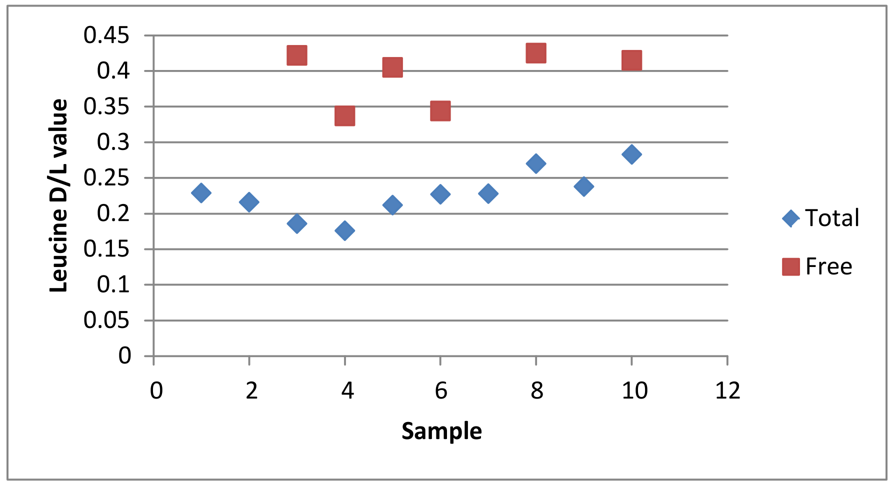
Plot of total and free amino acids from each sample for Valine

VAL	Total	Free
9853a1	0.109	
9853a2	0.103	
9853b1	0.105	0.149
9853b2	0.102	0.17
9853c1	0.114	0.163
9853c2	0.112	0.156
9853d1	0.117	
9853d2	0.099	0.118
9853 e1	0.118	
9853 e2	0.109	0.114



Plot of total and free amino acids from each sample for Leucine

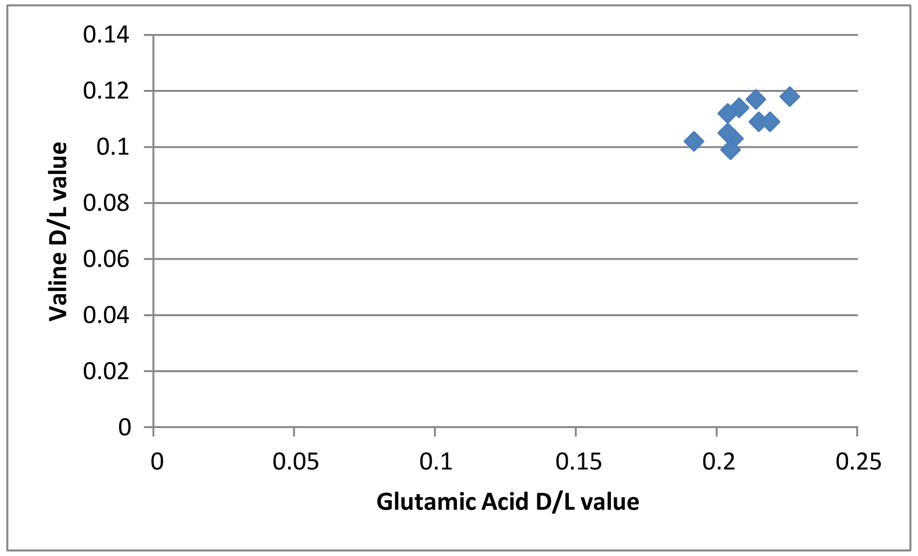
LEU	Total	Free
9853a1	0.229	
9853a2	0.216	
9853b1	0.186	0.422
9853b2	0.176	0.337
9853c1	0.212	0.405
9853c2	0.227	0.344
9853d1	0.228	
9853d2	0.27	0.425
9853 e1	0.238	
9853 e2	0.283	0.415



Note, 2 sub-samples taken from each individual shell. Sub-samples taken from around the apeture in all cases to avoid any intra-shell variation. Samples analysed for both total and free amino acids.

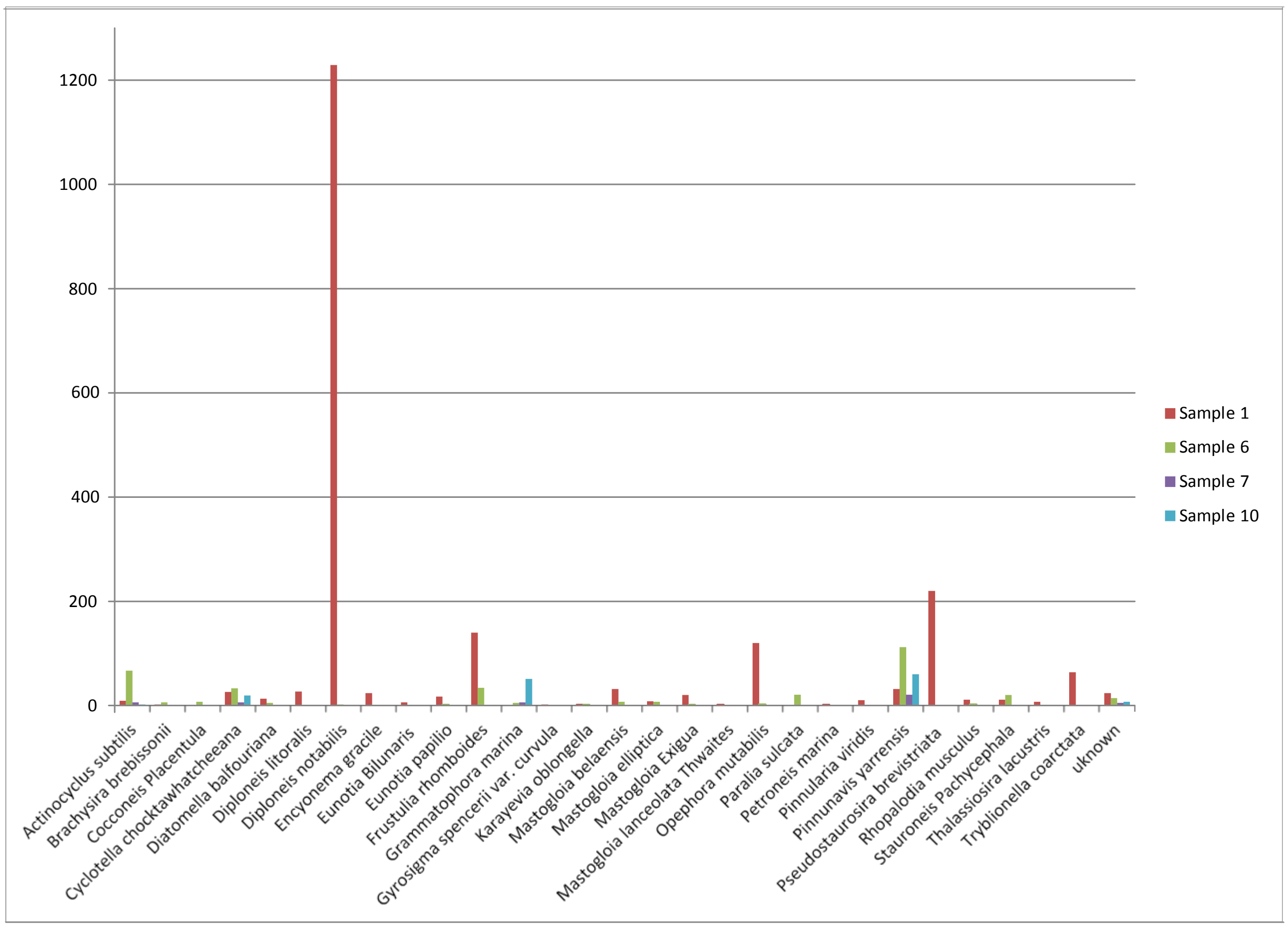
				Individual ages	Age	Error
PC 68cm	9853a1	0.642	0.640	5634	5597	38
	9853a2	0.638		5559		
PC 78 cm	9853b1	0.553	0.536	4070	3792	273
	9853b2	0.518		3524		
PC 127 cm	9853c1	0.62	0.657	5224	5913	711
	9853c2	0.693		6645		
PC 135 cm	9853d1	0.574	0.670	4416	6169	1899
	9853d2	0.765		8214		
PC 189 cm	9853 e1	0.698	0.751	6749	7896	1192
	9853 e2	0.804		9134		

Bivariate plot of Glutamic Acid and Valine



Appendix 3 – Diatom Species found in each sample

Diatom Species	Salinity Tolerances	Sample 1	Sample 6	Sample 7	Sample 10
Actinocyclus subtilis	Marine	9	67	6	2
Brachysira brebissonii	Fresh	2	6	0	0
Cocconeis Placentula	Fresh to hypersaline	1	7	0	0
Cyclotella chocktawhatcheeana	fresh to hypersaline	26	33	6	19
Diatomella balfouriana	Fresh to brackish	13	5	0	0
Diploneis litoralis	Brackish to marine	27	0	0	0
Diploneis notabilis	Fresh to brackish	1229	2	0	0
Encyonema gracile	Fresh	24	0	0	0
Eunotia Bilunaris	Fresh	6	0	0	0
Eunotia papilio	marine-hypersaline	17	3	0	0
Frustulia rhomboides	Fresh	140	34	0	0
Grammatophora marina	Marine	0	5	6	51
Gyrosigma spencerii var. curvula	Fresh to Brackish	2	0	0	0
Karayevia oblongella	Fresh to brackish	3	3	0	0
Mastogloia belaensis	Marine	32	7	0	0
Mastogloia elliptica	Brackish to marine	8	7	0	0
Mastogloia Exigua	marine to hypersaline	20	3	0	0
Mastogloia lanceolata Thwaites	Marine	3	0	0	0
Opephora mutabilis	Fresh to brackish	120	4	0	0
Paralia sulcata	Fresh to hypersaline	0	21	0	0
Petroneis marina	Marine	3	0	0	0
Pinnularia viridis	Fresh	10	0	0	0
Pinnunavis yarrensis	Marine	32	112	21	60
Pseudostaurosira brevistriata	Brakish	220	0	0	0
Rhopalodia musculus	Fresh to hypersaline	11	4	0	0
Stauroneis Pachycephala	Fresh-brackish	11	20	0	0
Thalassiosira lacustris	Fresh to brackish	7	0	0	0
Tryblionella coarctata	Brakish	64	0	0	0
uknown		24	14	5	7



Appendix 4

Metadata

School of Earth & Environmental Sciences
Simple Spatial Metadata Record

Spatial Analysis Laboratories

Dataset Title: Pattimore's Lagoon and Canal Areas 1950 -2011

Filename: Pattimores Lagoon and Canal Areas 1950 to 2011

This simple metadata template should be completed for every spatial dataset that is critical to your research project.

Each dataset submitted to SAL must be accompanied by a metadata record.

Abstract:

This image displays the outlines of Pattimore's Lagoon, the natural channel and artifical canal from images from 1950 - 2011 showing changes in the channel/canal area and lagoon edge.

Metadata Contact: Ashlee Clarke

Research Project Title:

The Environmental history and tidal regime of Pattimore's Lagoon, a modified coastal wetland

Suggested Search Words: Pattimore's Lagoon, 1950, 2011

Begin Date: 10/02/12 End Date: 20/10/12 Progress: Complete Updates: Not planned

Coordinate System: GDA_1994_MGA_Zone_56

west: 150.475 north: -35.265 south: -35.280 east: 150.488

Format: MapInfo TAB

Lineage - History of dataset creation:

This data set was created by first digisiting aerial photographs

-366-3 Ulladulla Run 87 Feb 1950 6" 1550
8927 Ulladulla at the Univeristy of Wollongong

-Ulladulla NSW1499 16.500 ASL 114-44 M.M from 18.3.1967:
8927 Ulladulla at the University of Wollongong

-NSW Coastline NSW 2016 20.000ASL 152.36 MM Run 13 04.06.1972
8927 Ulladulla at the University of Wollongong

-NSW Coastal Wetlands. 1:2500 Colour (MISC. 1309) NSW 2927 Run 67. 28.06.1981
8927 Ulladulla at the University of Wollongong

- Coastal Surveillance 2001. Stanwell Parak - Batemans Bay Conjola NSW 4550 (M2264). 17.04.2001
8927 Ulladulla at the University of Wollongong

-Ulladulla 1:25000 Approx. Scale NSW4595 (M2303) Run 8 20.01.2002:
8927 Ulladulla at the University of Wollongong

-Office and Environment and Heritage NSW. NSW South Coast VEK 3721c Run 29 15.05.2011

Photographs were georeferenced against an Orthodrectifed digital aerial image with Roads and rail spatial data from the NSW Digital Topographic Database (as of October 2009) used to assess accuracy.

Lineage - parent datasets:

Attribute Name	Attribute Type	Attribute Description
Lake Edge	Line	Tracing around the Lagoon edge
Canal Area	Line	Tracing around the Canal areas

Spatial Analysis Laboratories

Additional Information:

Fill out this template then print it to a PDF if you would like to create a digital 'final copy'

Print Form

School of Earth & Environmental Sciences

Simple Spatial Metadata Record

Dataset Title: Pattimore's Lagoon Delta Growth 1950- 2011

Filename: Pattimore's Lagoon Delta Growth 1950- 2011

This simple metadata template should be completed for every spatial dataset that is critical to your research project.

Each dataset submitted to SAL must be accompanied by a metadata record.

Abstract:

This image displays the area of Pattimore's Lagoon Delta from 1950- 2011, stacked to show the delta growth over time. Lagoon area is also present in each year to demonstrate changes.

Metadata Contact: Ashlee Clarke

Research Project Title: The Environmental history and tidal regime of Pattimore's Lagoon, a modified coastal wetland

Suggested Search Words: Pattimore's Lagoon, 1950, 2011

Begin Date: 10/02/12 End Date: 20/10/12 Progress: Complete Updates: Not planned

Coordinate System: GDA_1994_MGA_Zone_56

west: 150.475 north: -35.265 south: -35.280 east: 150.488

Format: MapInfo TAB

Lineage - History of dataset creation:

This data set was created by first digisiting aerial photographs

-366-3 Ulladulla Run 87 Feb 1950 6" 1550
8927 Ulladulla at the Univeristy of Wollongong

-Ulladulla NSW1499 16.500 ASL 114-44 M.M from 18.3.1967:
8927 Ulladulla at the University of Wollongong

-NSW Coastline NSW 2016 20.000ASL 152.36 MM Run 13 04.06.1972
8927 Ulladulla at the University of Wollongong

-NSW Coastal Wetlands. 1:2500 Colour (MISC. 1309) NSW 2927 Run 67. 28.06.1981
8927 Ulladulla at the University of Wollongong

- Coastal Surveillance 2001. Stanwell Parak - Batemans Bay Conjola NSW 4550 (M2264). 17.04.2001
8927 Ulladulla at the University of Wollongong

-Ulladulla 1:25000 Approx. Scale NSW4595 (M2303) Run 8 20.01.2002:
8927 Ulladulla at the University of Wollongong

-Office and Environment and Heritage NSW. NSW South Coast VEK 3721c Run 29 15.05.2011

Photographs were georeferenced against an Orthodrectifed digital aerial image with Roads and rail spatial data from the NSW Digital Topographic Database (as of October 2009) used to assess accuracy.

Lineage - parent datasets:

Attribute Name	**Attribute Type**	**Attribute Description**
Lake Edge	Line	Tracing around the Lagoon edge
Delta area	Polygon	Tracing to the delta extent in each image

Spatial Analysis Laboratories

Additional Information:

Fill out this template then print it to a PDF if you would like to create a digital 'final copy'

Print Form

School of Earth & Environmental Sciences
Simple Spatial Metadata Record

Spatial Analysis Laboratories

Dataset Title: Pattimore's Lagoon Treeline 1950-2011

Filename: Pattimore's Lagoon Treeline 1950- 2011

This simple metadata template should be completed for every spatial dataset that is critical to your research project.

Each dataset submitted to SAL must be accompanied by a metadata record.

Abstract:

This image displays the the edge of treeline, defined at the point in which only treecover can be recoginsed.

Metadata Contact: Ashlee Clarke

Research Project Title: The Environmental history and tidal regime of Pattimore's Lagoon, a modified coastal wetland

Suggested Search Words: Pattimore's Lagoon, 1950, 2011

Begin Date: 10/02/12 End Date: 20/10/12 Progress: Complete Updates: Not planned

Coordinate System: GDA_1994_MGA_Zone_56

west: 150.475 north: -35.265 south: -35.280 east: 150.488

Format: MapInfo TAB

Lineage - History of dataset creation:

This data set was created by first digisiting aerial photographs

-366-3 Ulladulla Run 87 Feb 1950 6" 1550
8927 Ulladulla at the Univeristy of Wollongong

-Ulladulla NSW1499 16.500 ASL 114-44 M.M from 18.3.1967:
8927 Ulladulla at the University of Wollongong

-NSW Coastline NSW 2016 20.000ASL 152.36 MM Run 13 04.06.1972
8927 Ulladulla at the University of Wollongong

-NSW Coastal Wetlands. 1:2500 Colour (MISC. 1309) NSW 2927 Run 67. 28.06.1981
8927 Ulladulla at the University of Wollongong

- Coastal Surveillance 2001. Stanwell Parak - Batemans Bay Conjola NSW 4550 (M2264). 17.04.2001
8927 Ulladulla at the University of Wollongong

-Ulladulla 1:25000 Approx. Scale NSW4595 (M2303) Run 8 20.01.2002:
8927 Ulladulla at the University of Wollongong

-Office and Environment and Heritage NSW. NSW South Coast VEK 3721c Run 29 15.05.2011

Photographs were georeferenced against an Orthodrectifed digital aerial image with Roads and rail spatial data from the NSW Digital Topographic Database (as of October 2009) used to assess accuracy.

Lineage - parent datasets:

Attribute Name	Attribute Type	Attribute Description
Treeline	Line	Tracing around the edge of the distinguishable treeline.

Spatial Analysis Laboratories

Additional Information:

Fill out this template then print it to a PDF if you would like to create a digital 'final copy'

Print Form